ENERGY FROM WASTE: REVIEW OF THERMOCHEMICAL TECHNOLOGIES FOR REFUSE DERIVED FUEL (RDF) TREATMENT

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SUMMARY: The growing amount of municipal solid waste (MSW) and the related problems of waste disposal urge the development of a more sustainable waste management practice. Waste-to-Energy (WtE) technologies – recovering energy in the form of electricity and/or heat from waste – are being developed worldwide. The present paper reviews thermochemical technologies for energetic valorization of calorific waste streams (WtE), with focus on refuse derived fuel (RFD) – a processed form of municipal solid waste (MSW). The basic principles of the available technologies and process details of some specific technologies are summarized. Technologically advanced processes (e.g. plasma gasification) receive more attention, with particular focus on the potential for energy recovery (WtE) and material recovery (WtP). The review concludes with an argumentation of the advantages of processing RDF as opposed to MSW, and a comparison between the different technologies, stressing factors affecting their applicability and operational suitability.

1. INTRODUCTION

In accordance with Lansink's stepladder – setting the following priority for waste management: prevention > recycling > incineration with energy recovery > incineration > landfilling – waste management has evolved to a stronger focus on material recuperation and recycling (e.g. glass, paper, etc.), and waste prevention. Nevertheless, despite increasing attention for prevention and sustainability, total municipal solid waste (MSW) generation in the EU25 has increased from about 150 million tonnes in 1980 to more than 250 million tonnes in 2005 and is forecasted to reach 300 million tonnes by 2015 (ETC/RWM, 2007). Although it will become increasingly difficult to find the required space for new landfills and to get the permission for their construction, the phase out of landfilling will be a long haul. The key reasons are: the limited available capacity of waste treatment plants such as incineration plants combined with the continually growing amount of MSW, a lack of suitable techniques to treat all types of wastes, and no sound economic balance.

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Waste-to-Energy (WtE) technologies have over the past decade received increased attention as part of the development of a more sustainable waste management practice. Waste-to-Energy is the process of recovering energy, in the form of electricity and/or heat, from waste. Municipal solid waste is a heterogeneous feedstock containing materials with widely varying sizes, shapes and composition. If the MSW is used in an as received condition as input to WtE processes, this can lead to variable (and even unstable) operating conditions, resulting in product quality fluctuations. For this reason, refuse derived fuel (RDF) – a processed form of MSW – is often used as input to WtE systems. In general, the process of converting MSW into RDF consists of shredding, screening, sorting, drying and/or pelletization in order to improve the handling characteristics and homogeneity of the material. The resulting fuel has a significantly higher energy density than the crude municipal waste. Therefore, a trade-off between the increased costs of producing RDF from MSW and potential cost reductions in system design and operation needs to be found.

The review presented in this paper focuses on thermochemical WtE technologies for RDF treatment since many conversion technologies — such as gasification or pyrolysis — require a homogeneous input. The technology analysis includes a process description along with process limitations, in addition to actual and potential applications. The evaluation criteria are based on environmental impact, energy balances, material recuperation and system operation (e.g. flexibility in dealing with input variation). This review constitutes the base for selecting best available technique(s) for RDF treatment. Attention is paid to the specific advantages the selected technologies offer with regard to RDF treatment, as opposed to MSW treatment. Furthermore, a closer look is taken at technologies offering the added benefit of recovering materials – in addition to energy – from the waste feed. In the Waste-to-Product (WtP) concept, waste treatment by-products are used to manufacture valuable (i.e. saleable) coproducts.

Differences in technology maturity need to be kept in mind when comparing and evaluating the available technologies. This review is limited to technologies that have been commercially proven in a full-scale plant, or that have at least been demonstrated through pilot plant testing.

2. THERMOCHEMICAL CONVERSION TECHNOLOGIES

As shown in Figure 1, WtE technologies can be divided into different categories. The conventional approach for energetic valorization of waste is direct combustion or incineration, generating directly heat. Besides in cineration more advanced thermochemical approaches, such as pyrolysis, gasification and plasma-based technologies, have been developed since the 1970s (Kolb and Seifert, 2002). In general these alternative technologies have been applied to selected waste streams and on a smaller scale than incineration, and attempt to control process temperatures and pressures in specially designed reactors. In a first step the waste is converted into a secondary energy carrier (a combustible liquid, gas or solid product), while in a second step this secondary energy carrier is burned (in a steam turbine, gas turbine or gas engine) in order to produce heat and/or electricity. The conversion of solid wastes into secondary energy carriers allows for a cleaner and more efficient process. Smaller flue gas volumes allow reduced gas cleaning equipment sizes. Furthermore, it enables a greater market penetration since these secondary energy carriers are compatible with gas turbines and gas motors, characterized by a high electrical efficiency.

Both pyrolysis and gasification differ from incineration in that they may be used for recovering the chemical value from the waste, rather than its energetic value.

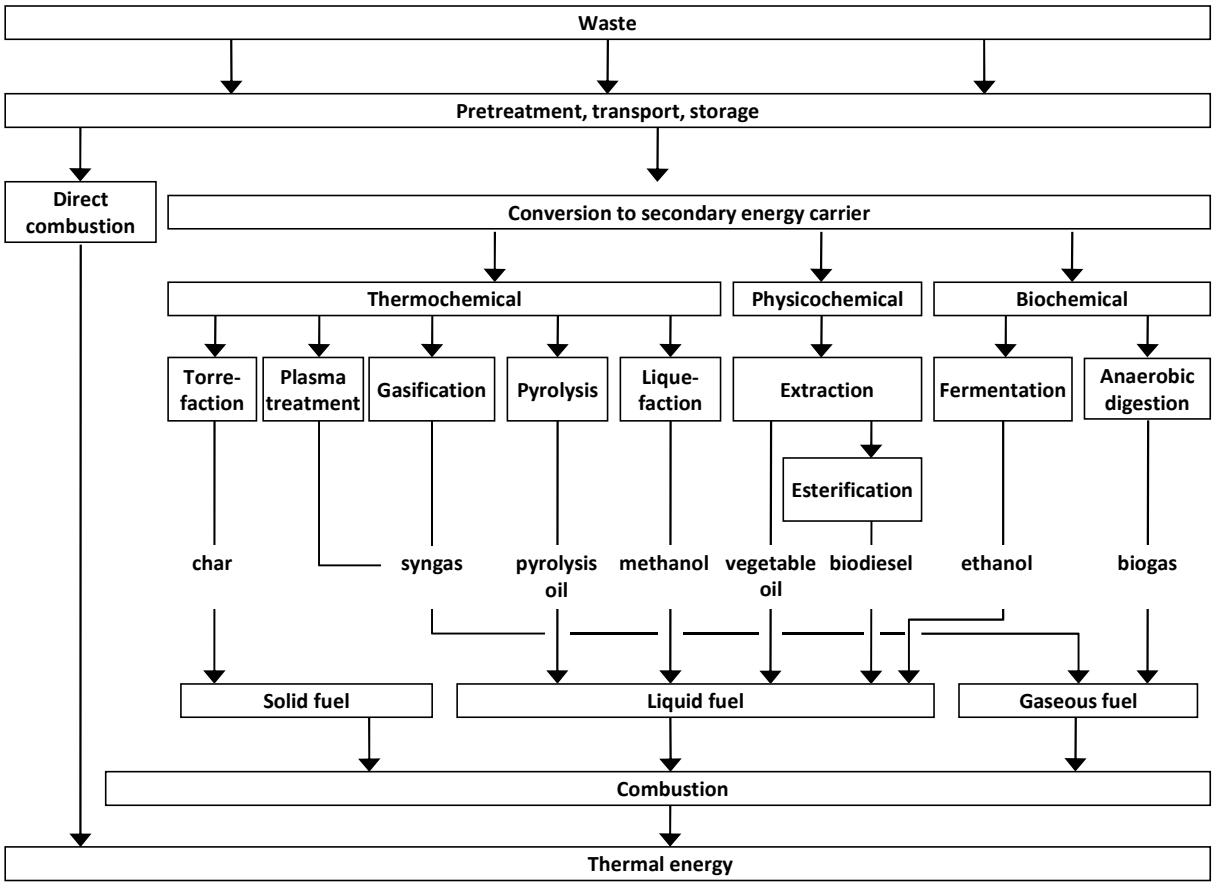

Figure 1. Waste-to-Energy technologies (Kaltschmitt and Reinhardt, 1997).

The chemical products derived may in some cases then be used as feedstock for other processes or as a secondary fuel. However, when applied to wastes, pyrolysis, gasification and combustion based processes are often combined, usually on the same site as part of an integrated process.

When this is the case the installation is, in total, generally recovering the energy value rather than the chemical value of the waste, as would a conventional incinerator do.

The scope of this paper is to compare and evaluate different thermochemical valorization techniques for high calorific waste streams (represented by RDF). Five main types of thermochemical waste treatment techniques are discussed:

- Pyrolysis – thermal degradation of organic material in the absence of oxygen,
- Gasification – partial oxidation,
- Incineration – full oxidative combustion,
- Plasma-based technologies – combination of (plasma-assisted) pyrolysis/gasification of the organic fraction and plasma vitrification of the inorganic fraction of waste feed.
- Combination processes – combination of different thermochemical processes

Incineration is by far the most widely applied; the degree of demonstration (as measured by overall throughput and operational hours) of pyrolysis and gasification on the main European waste streams is low compared to incineration. The reaction conditions for these thermal treatments vary, but may be differentiated as indicated in Table 1.

2.1 Incineration

The objective of waste incineration, in common with most waste treatments, is to treat waste to reduce its volume and hazardous characteristics, hereby capturing (and thus concentrating) or destroying potentially harmful substances. Incineration processes can also provide a means to enable recovery of the energy, mineral and/or chemical content of waste.

The incineration sector has undergone rapid technological development over the last 10 to 15 years. Much of this change has been driven by legislation specific to the industry and this has, in particular, reduced emissions to air from individual installations. Continuous process development is ongoing, with the sector developing techniques which limit operating costs and at the same time maintaining or improving environmental performance.

Incineration is used as a treatment for a very wide range of wastes. Basically, incineration is the oxidation of the combustible materials contained in the waste. Waste is generally a highly heterogeneous material, consisting essentially of organic substances, minerals, metals and water. During incineration, flue gases are generated that contain the majority of the available fuel energy as heat. The organic waste substances burn when they have reached the ignition temperature and come into contact with oxygen. The actual combustion process takes place in the gas phase in fractions of seconds and simultaneously releases energy.

Table 1 - Typical reaction conditions and products from pyrolysis, gasification and incineration processes, based on (Kolb and Seifert, 2002).

	Pyrolysis	Gasification	Combustion	Plasma treatment
Temperature [°C]	250-900	500-1800	800-1450	1200-2000
Pressure [bar]	1	1-45	1	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air	Gasification agent: O_2, H_2O Plasma gas: O_2, N_2, Ar
Stoichiometric ratio	0	< 1	> 1	< 1
Products from the process:				
Gas phase	H_2, CO, H_2O, N_2, hydrocarbons	H_2, CO, CO_2, CH_4, H_2O,N_2	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2
Solid phase	Ash, coke	Slag, ash	Ash, slag	Slag, ash
Liquid phase	Pyrolysis oil and water			

Where the heating value of the waste and oxygen supplyare sufficient, this can lead to a thermal chain reaction and self-supporting combustion, i.e. there is no need for the addition of other fuels (BREF, 2006).

The main stages of the incineration process are: drying and degassing, pyrolysis and gasification, oxidation. These individual stages generally overlap, meaning that spatial and temporal separation of these stages during waste incineration may only be possible to a limited extent. Nevertheless it is possible to influence these processes so as to reduce pollutant emissions, for example by using measures such as furnace design, air distribution and control engineering.

For effective oxidative combustion, a sufficient oxygen supply is essential. The air ratio number of the supplied incineration air to the chemically required (or stoichiometric) incineration air, usually ranges from 1.2 to 2.5, depending on whether the fuel is gas, liquid or solid, and the furnace system. Waste incinerators receive a waste feed with a certain heating value. In a large majority of cases, the energetic content of the waste exceeds the process requirements which may result in the net generation of heat. Municipal solid waste incinerators in particular, offer a large potential source of energy, especially in the case where combined heat and power (CHP) is applied.

The size of incineration installations varies significantly across Europe. Variations in size can be seen within and between technology and waste types. The average capacity of MSW plants in Europe equals 193 kton per year (BREF, 2006). The basic linear structure of a waste incineration plant is presented in Figure 2 and may include the following operations (UBA, 2001):

- incoming waste reception,
- storage of waste and raw materials,
- pretreatment of waste (where required, on-site or off-site),
- loading of waste into the process,
- thermal treatment of the waste,
- energy recovery (e.g. boiler) and conversion,
- flue gas cleaning / residue management / discharge,
- emissions monitoring and control,
- waste water control and treatment (e.g. from site drainage, flue gas treatment, storage),
- (bottom) ash management and treatment (arising from the combustion stage), solid residue discharge/disposal.

The detailed design of a waste incineration plant will change according to the type of waste that is being treated. Key drivers are the chemical composition, physical and thermal characteristics of the waste together with the variability of these parameters.

Processes designed for a narrow range of specific inputs can usually be optimized to a larger extent than those that receive wastes with greater variability. This in turn enables improvements to be made in process stability and environmental performance, and may allow a simplifying of downstream operations such as flue gas cleaning. As flue gas cleaning is often an important contributor to overall incineration costs (i.e. 15 to 35 % of the total capital investment) this can lead to a significant cost reduction. The external costs of pretreatment, or the selective collection of certain wastes, can however add substantially to the overall costs of waste management and to emissions from the entire waste management system.

In fully oxidative incineration the main constituents of the flue gas are water vapour, nitrogen, carbon dioxide and oxygen. Depending on the composition of the material incinerated and on the operating conditions, smaller amounts of CO, HCl, HF, HBr, HI, NOX, SO2, VOCs, PCDD/F, PCBs and heavy metal compounds (among others) are formed or remain (BREF, 2006).

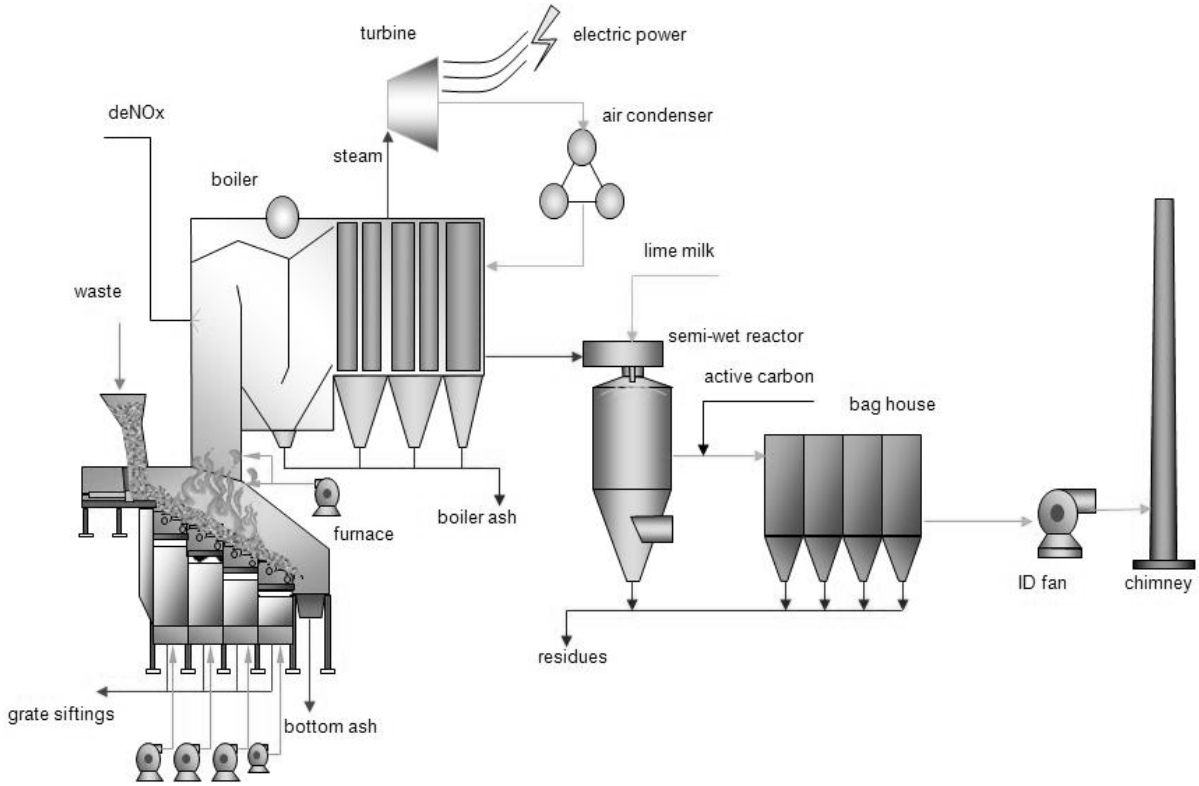

Figure 2. Example layout of a MSW incineration plant, starting from waste loading (BIC, 2010).

Depending on the combustion temperatures during the main stages of incineration, volatile heavy metals and inorganic compounds (e.g. salts) are totally or partly evaporated. These substances are transferred from the input waste to both the flue gas and the fly ash.

The types and quantities of produced residues vary greatly according to the installation design, its operation and waste input; the most commonly produced residues during the incineration process are fly and bottom ash, slag, filter dust, other residues from the flue gas cleaning (e.g. calcium or sodium chlorides) and sludge from waste water treatment.

Some thermal treatment residues (mostly vitrified slags from very high temperature processes) can be used directly without treatment. Bottom ash constitutes approximately 25 to 30 % by weight of the solid waste input. Additional treatment can improve bottom ash characteristics and would allow its use in concrete aggregates. Fly ash quantities are much lower, generally 1 to 5 % of the input (EMIS, 2010). Fly ash immobilization is required in order to make it environmentally safe for landfill disposal. Furthermore, residues produced from the flue gas cleaning are an important source of waste production. The amount and nature of these vary mainly according to the types of waste being incinerated and the technology employed.

The following sections describe the three main incinerator types: grate incinerators, rotary kilns and fluidized beds.

2.1.1 Grate incinerators

Grate incinerators are widely applied for the incineration of mixed municipal wastes. In Europe, approximately 90 % of the incinerators treating MSW use grates. Other wastes commonly treated in

grate incinerators, often in addition with MSW, include commercial and industrial non hazardous wastes, sewage sludge and certain clinical wastes. The principal reason for the wide adoption of the grate combustion technology is its relative simplicity. Additionally, it can handle a wide range of object sizes.

The typical grate incinerator (shown in Figure 2) consists of the following components: waste feeder, incineration grate, bottom ash discharger, incineration air duct system, incineration chamber and auxiliary burners.

2.1.2 Rotary kilns

Rotary kilns are very robust and allow almost any waste, regardless of type and composition, to be incinerated. Rotary kilns are widely applied for the incineration of hazardous wastes and are also commonly used for clinical wastes, but less for municipal wastes.

Operating temperatures of rotary kilns range from around 500 °C (as a gasifier) to 1450 °C (as a high temperature ash melting kiln). When used for conventional oxidative combustion, the temperature is generally above 850 °C. Temperatures in the range 900-1200 °C are typical when incinerating hazardous wastes. Figure 3 displays the schematic presentation of a rotary kiln incineration system.

The rotary kiln consists of a cylindrical vessel slightly inclined on its horizontal axis. The vessel is usually located on rollers, allowing the kiln to rotate or oscillate around its axis (reciprocating motion). The waste is conveyed through the kiln by gravity as it rotates. Solid waste, liquid waste, gaseous waste, as well as sludge can be incinerated in rotary kilns. Direct injection is used particularly for liquid, gaseous or pumpable wastes, especially where they have safety risks. The residence time of the solid material in the kiln is determined by the horizontal angle of the vessel and the rotation speed. A residence time of between 30 to 90 minutes is normally sufficient to achieve good waste burnout. In order to increase the destruction of toxic compounds, a post-combustion chamber is usually added.

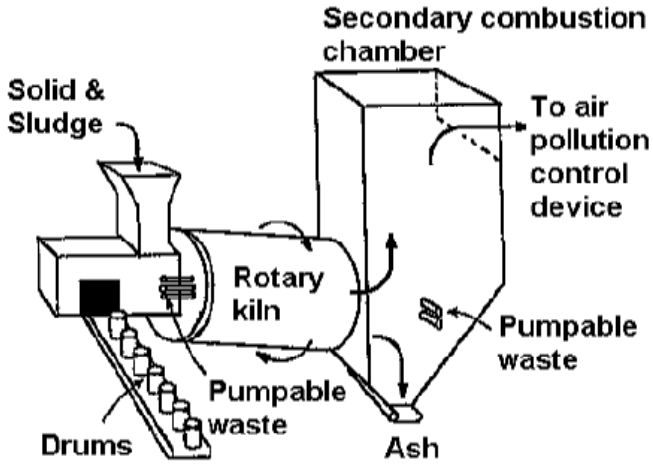

Figure 3. Schematic presentation of rotary kiln incineration system (BREF, 2006).

Additional firing using liquid waste or additional fuel may be carried out to maintain the temperatures required to ensure the destruction of the waste being incinerated.

Refuse derived fuel can serve as alternative fuel in rotary kiln cement plants by supplying part of the thermal energy demand required for the process. It is reported that RDF can replace fossil fuels up to a level of more than 80 % in some plants (BREF, 2010). The added value of using wastes in cement kilns is twofold; the thermal energy as well as the material value of the waste input is recovered in the process. In order to guarantee the desired product quality, a constant waste quality is essential.

2.1.3 Fluidized beds

Fluidized bed incinerators are widely applied to the incineration of finely divided wastes (e.g. RDF and sewage sludge). It has been used for decades, mainly for the combustion of homogeneous fuels such as coal, raw lignite, sewage sludge and biomass (e.g. wood). The fluidized bed incinerator is a lined combustion chamber in the form of a vertical cylinder. In the lower section, a bed of inert material (e.g. sand or ash) on a grate or distribution plate is fluidized with air. The waste for incineration is continuously fed into the fluidized sand bed from the top or side (UllmannsEncyclopedia, 2001). Preheated air is introduced into the combustion chamber through holes in the bed-plate, forming a fluidized bed with the sand contained in the combustion chamber.

In the fluidized bed, drying, volatilization, ignition, and combustion take place. The temperature in the free space above the bed (the freeboard) is generally between 850 and 950 °C. Above the fluidized bed material, the freeboard is designed to allow retention of the gases in a combustion zone. In the bed itself the temperature is lower, and may be around 650 °C or higher.

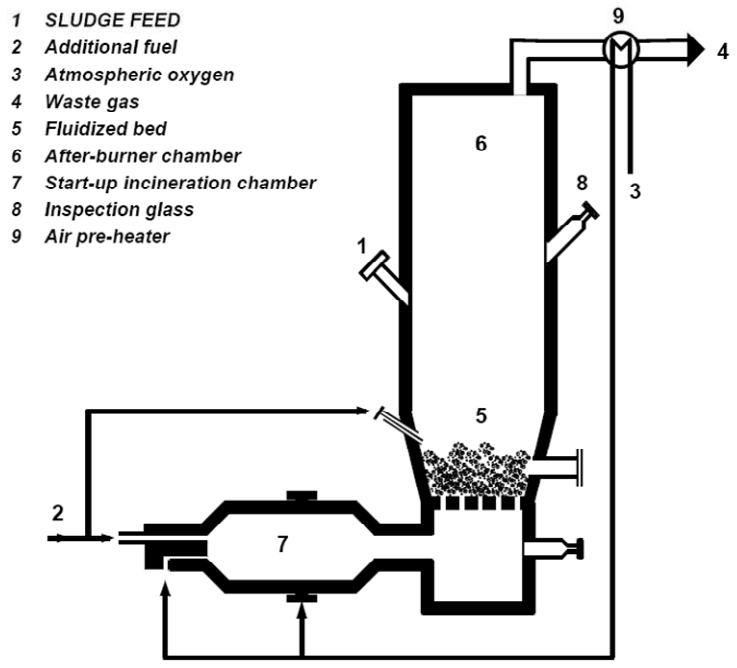

Figure 4. Process schematic of a stationary/bubbling fluidized bed incinerator (UBA, 2001).

Because of the well-mixed nature of the reactor, fluidized bed incineration systems generally have a uniform distribution of temperatures and oxygen, which results in stable operation.

For heterogeneous wastes, fluidized bed combustion requires a preparatory process step for the waste so that it conforms to size specifications. For some wastes this may be achieved by a combination of selective collection of wastes and/or pretreatment such as shredding. The particle size of the waste must be small, often with a maximum diameter of 50 mm. Some types of fluidized beds can receive larger particle size wastes than others, it is reported that average acceptable diameters for rotating fluidized beds are 200-300 mm (Limerick, 2005).

During incineration the fluidized bed contains the unburned waste and the ash produced. The ash surplus is usually removed at the bottom of the furnace (UBA, 2001; BREF, 2006).The heat produced by the combustion can be recovered by devices either integrated inside the fluidized bed or at the exit of the combustion gases or a mixture of layouts. The relatively high cost of pretreatment processes required for some wastes has restricted the economic use of these systems to larger scale projects. The following fluidized bed furnace technologies can be differentiated according to the gas speeds and design of the nozzle plate:

- Stationary (or bubbling) fluidized bed (atmospheric and pressurised): the inert material is mixed, but the resulting upwards movement of solids is not significant (see Figure 4). This type of fluidized bed is commonly used for sewage sludge, as well as for other industrial sludge (e.g. petrochemical and chemical industry sludge).
- A type of bubbling fluidized bed is the rotating fluidized bed: the fluidized bed is rotated in the incineration chamber, which results in a longer residence time in the incineration chamber. Rotating fluidized bed incinerators are used for mixed municipal wastes.
- Circulating fluidized bed: the higher gas speeds in the combustion chamber are responsible for partial removal of the fuel and bed material, which is fed back into the incineration chamber by a re-circulation duct. The circulating fluidized bed (see Figure 5) is especially appropriate for the incineration of dried sewage sludge with a high heating value. The waste falls into the fluidized bed, where it is crushed through abrasion and incineration. Usually, the major part of the ash is transported with the flue gas flow and requires separation in flue gas treatment equipment.

2.2 Gasification

Gasification is the thermochemical conversion of carbon-based materials into a combustible gaseous product (synthesis gas or syngas). In general, it involves the reaction of carbonaceous materials with air, oxygen, steam, carbon dioxide, or a mixture of these gases at 500-1800 °C or higher. Air gasification produces a low heating value (LHV) gas (4-7 MJ/Nm^3 higher heating value), while oxygen gasification produces a medium heating value (MHV) gas (10-18 MJ/Nm^3 higher heating value) (Helsen, 2000). The syngas contains CO_2, CO, H_2, CH_4, H_2O, trace amounts of higher hydrocarbons, inert gases originating from the gasification agent, various contaminants such as small char particles, ash and tars (Bridgwater, 1994). The syngas can be used for efficient production of electricity and/or heat, or second generation liquid biofuels.

Several different gasification processes are available or being developed which are in principle suited for the treatment of MSW, certain hazardous wastes and dried sewage sludge. The nature (size, consistency) of the waste input should remain within certain predefined limits to ensure adequate gas-solid contact resulting in maximal conversion of carbonaceous material into CO and H_2 and thus minimal tar formation. Typically, this requires preprocessing of MSW, thereby increasing the cost.

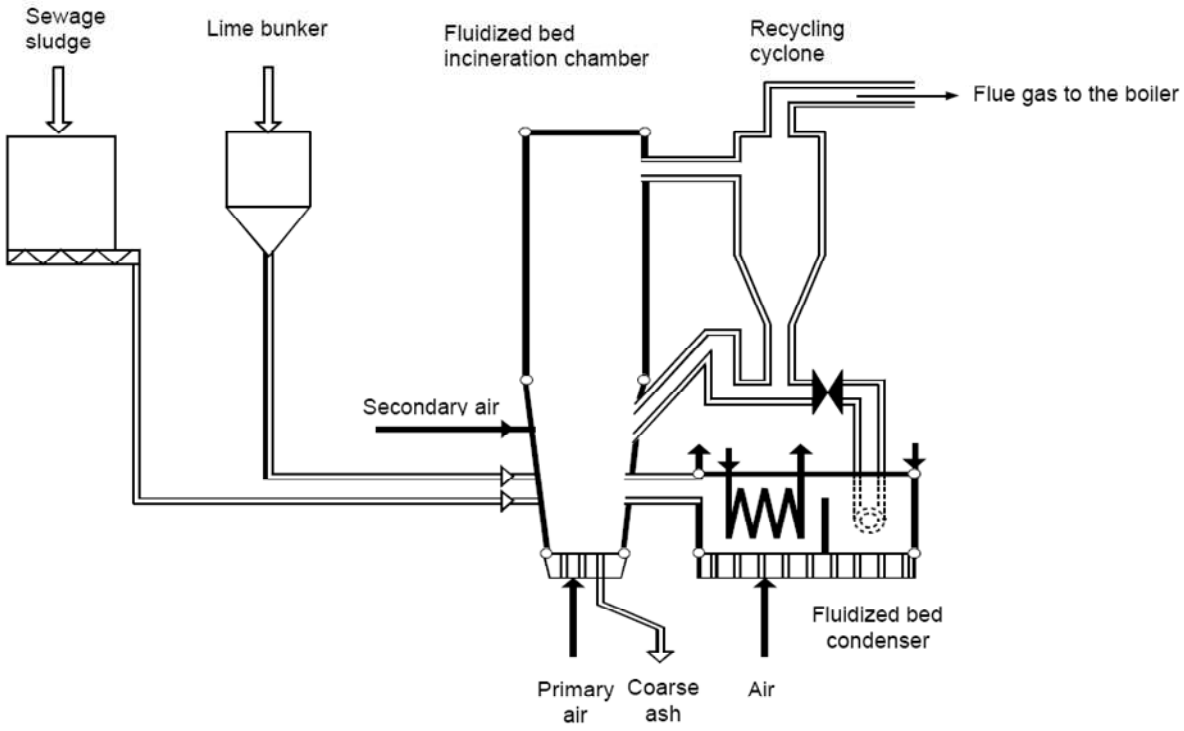

Figure 5. Process schematic of a circulating fluidized bed incinerator (UBA, 2001).

Advantages of gasification processes include:

- smaller gas volume compared to incineration (up to a factor of 10 by using pure O_2),
- smaller waste water flows from synthesis gas cleaning,
- predominant formation of CO rather than CO_2,
- capturing of inorganic residues, e.g. within slag in high temperature slagging gasifiers,
- high operating pressures (in some processes), leading to small and compact aggregates,
- material and energetic utilization of the synthesis gas.

There are four main types of gasification reactors used in practice: entrained flow gasifier, fluidized bed gasifier, cyclone gasifier and packed bed gasifier. The feedstock (waste) material must be finely granulated for utilization in entrained flow, fluidized bed or cyclone gasifiers. Consequently, pretreatment is necessary, especially for MSW. Hazardous wastes may be gasified directly if they are liquid or finely granulated.

2.2.1 Examples of gasification processes

At present, an *entrained flow gasifier* is in use for the gasification of fluid hazardous wastes at SVZ Schwarze Pumpe GmbH (Germany). The fluid waste enters into the reactor through the burner system and is transformed into synthesis gas at temperatures of 1600-1800 °C. Since 1995, approximately 31,000 ton of waste oil has been treated in this plant (UBA, 2001).

Moreover, SVZ Schwarze Pumpe GmbH runs six *packed bed gasifiers* for treatment of coal-waste mixtures. The feed rate proportion for waste amounts up to 85 %. The reactors – each with a capacity of 8-14 ton per hour – mainly treat compacted waste plastics, dehydrated sewage sludge and contaminated soils. The waste enters into the reactor through the entry lock and is transformed

into synthesis gas at approximately 800-1300 °C and 25 bar by using steam and oxygen as gasification agent) (UBA, 2001).

The *slag bath gasifier* is a further development of these packed bed gasifiers. Figure 6 shows a slag bath gasifier – currently operating on a trial basis – receiving up to 70 % waste at a throughput rate of 30 ton per hour (UBA, 2001). The gasifier operates at a temperature of up to 1600 °C and the slag is discharged as a liquid.

A waste gasification process consisting of *the combination of a fluidized bed and an entrained flow reactor* (see Figure 7) is used in Japan to generate synthesis gas from plastic packaging waste or other high calorific waste material. The main components of the process are the (low temperature) fluidized bed gasifier and the second stage (high temperature) entrained flow gasifier. The fluidized bed enables rapid gasification of rather heterogeneous materials, which are pelletized for smooth feeding. Several percent of non-combustible components, even metal pieces, are acceptable, as the ash is continuously discharged from the fluidized bed.

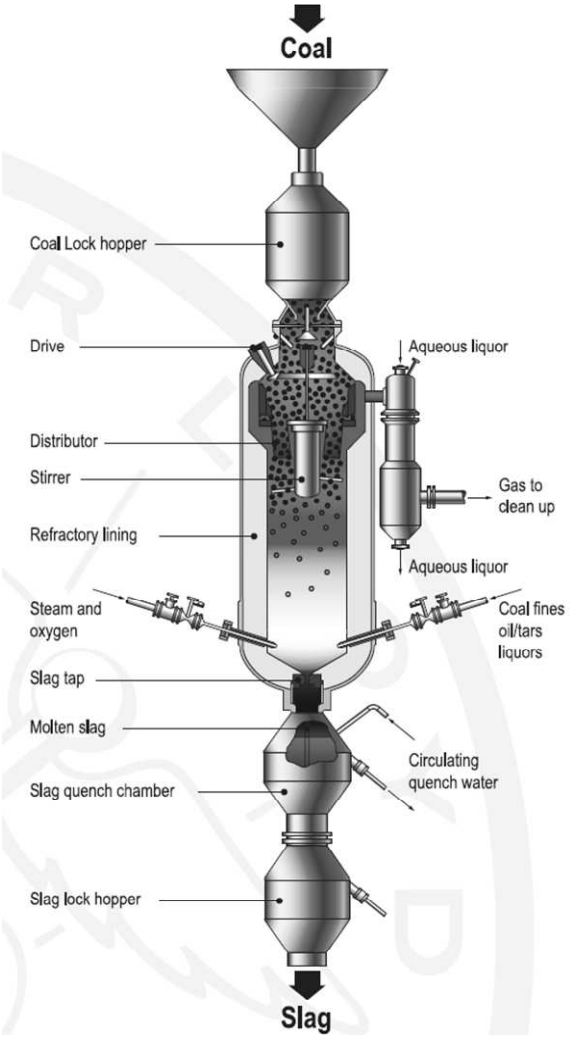

Figure 6. Slag bath gasifier (GL, 2009)

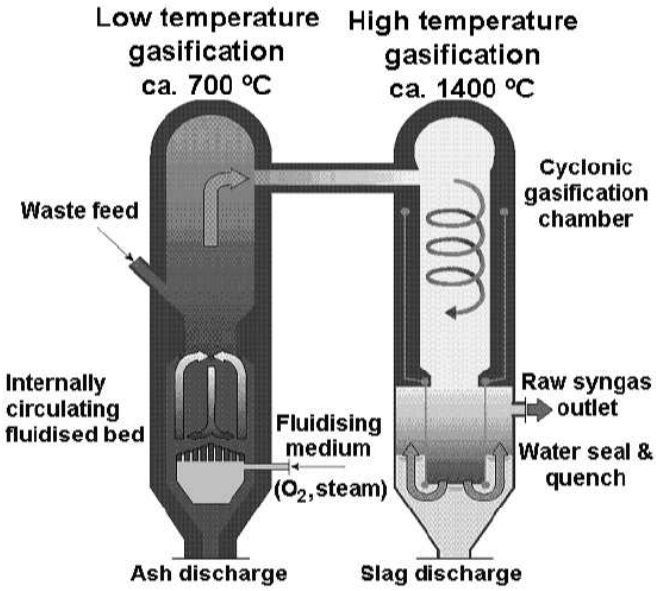

Figure 7. Fluidized bed gasifier with high temperature slagging furnace (EBARA, 2003).

The high temperature gasifier is designed as a cyclone, to collect the fine ash particles on the wall. After vitrification, the slag is discharged through a water seal. Both reactors are operated under elevated pressure, typically 8 bar. A first plant of this technology was under commercial operation in 2001 to treat plastic packaging waste. The capacity of this demonstration plant is 30 ton per day. An additional plant of 65 ton per day started operation in 2002. The synthesis gas produced is fed to an adjacent ammonia production plant. Other similar plants are under construction (EBARA, 2003).

Other variations on gasification processes have been tried and are being developed, for a variety of waste stream. Examples can be found in (Bridgewater, 2003).

2.3 Pyrolysis

Pyrolysis is thermal degradation either in the complete absence of an oxidizing agent, or with such a limited supply that gasification does not occur to an appreciable extent; the latter may be described as partial gasification and is used to provide the thermal energy required for pyrolysis at the expense of product yields. Relatively low temperatures (400-900 °C, but usually lower than 700 °C) are employed compared to gasification. Three products are obtained: pyrolysis gas, pyrolysis liquid and solid coke, the relative proportions of which depend very much on the pyrolysis method and reactor process parameters. The characteristics of the main modes of pyrolysis are summarized in Table 2 (Bridgwater and Bridge, 1991; Bridgwater, 1995). The heating values of pyrolysis gas typically lie between 5 and 15 MJ/m³ based on MSW and between 15 and 30 MJ/m³ based on RDF (UBA, 2001).

A pyrolysis plant for MSW treatment is operational in Germany. Other pyrolysis projects exist in Europe and elsewhere (notably in Japan) receiving certain specific types or fractions of waste, often after pretreatment. Pyrolysis plants for waste treatment usually include the following basic process stages:

- Preparation and grinding: the grinder improves and standardizes the quality of the waste presented for processing and so promotes heat transfer.
- Drying (depends on process): a separated drying step improves the lower heating value of the raw process gases and increases efficiency of gas-solid reactions within the rotary kiln.
- Pyrolysis of wastes: in addition to the pyrolysis gas, a solid carbon-containing residue accumulates which also contains mineral and metallic portions.
- Secondary treatment of pyrolysis gas and pyrolysis coke: through condensation of the gases for the extraction of energetically usable oil mixtures and/or incineration of gas and coke for the destruction of the organic ingredients and simultaneous utilization of energy.

In addition to the thermal treatment of MSW and sewage sludge, pyrolysis processes are also used for decontamination of soil, treatment of synthetic waste and used tyres, treatment of cable tails as well as metal and plastic compound materials for substance recovery.

Conventional pyrolysis reactors have one of the following configurations: fixed bed, fluidized bed, entrained flow, moving bed, rotary kiln, ablative reactor, etc., and often require waste pretreatment. The interaction between a large number of thermochemical phenomena results in a large diversity of substances obtained and increases the complexity of the process. Several hundred different compounds are produced during waste pyrolysis, and many of these have not yet been identified. A thorough understanding of the characteristics and concentration of effluents to be processed is essential, especially when hazardous substances are concerned (Helsen, 2000). The usefulness of pyrolysis for secondary fuel production or substance recovery from waste depends on the presence of potential pollutants, which could make the pyrolysis products useless, or at least difficult to use.

Table 2 - Pyrolysis technology variants (RT and HR stand for residence time and heating rate, respectively).

Pyrolysis technology	RT	HR	T_{max} [°C]	Product
Carbonisation	hours-days	very low	400	charcoal
Slow	5-30 min	low	600	Charcoal pyrolysis oil gas
Fast	0.5-5 s	fairly high	650	pyrolysis oil
Flash *Liquid* *Gas*	 < 1 s < 1 s	 high high	 < 650 > 650	pyrolysis oil Chemicals fuel gas
Ultra	< 0.5 s	very high	1000	chemicals□fuel gas
Vacuum	2-30 s	medium	400	pyrolysis oil
Hydropyrolysis	< 10 s	high	< 500	pyrolysis oil chemicals
Methanopyrolysis	< 10 s	high	> 700	chemicals

Pyrolysis processes offer a number of advantages:

- possibility of recovering (part of) the organic fraction as material/fuel (e.g. as methanol),
- possibility of more efficient electricity generation using gas engines or gas turbines (instead of steam boilers),
- reduced flue gas volumes after combustion, which may reduce the flue gas treatment capital costs to some degree,
- possibility of recovering the char for external use, after pretreatment (e.g. washing of chlorine).

2.3.1 Example of pyrolysis in combination with a power plant

The ConTherm pyrolysis plant is designed to be added to an existing power plant. It consists of two lines of drum-type kilns with a scheduled annual MSW throughput of 50 kton each. The kilns operate at 450-550 °C in the absence of oxygen, producing coke, pyrolysis gas, metals (appearing in metallic form which allows collection at high purity) and inert materials within a residence time of 1 hour. The solid residue is separated into a coarse fraction (metals, inerts) and a fine fraction, containing 99 % of the carbon as coke. After sieving, the coarse fraction is supplied to a wet ash remover, cooled and directed to a reprocessing plant separating the coarse fraction into ferrous and non-ferrous metals. The resulting pyrolysis gas consists of vaporized H_2O, CO, H_2, CH_4 and higher carbohydrates. A cyclone de-dusts the pyrolysis gas, after which the deposited dusts and carbon particles are added to the pyrolysis coke.

The existing boiler unit is supplied with pyrolysed substitute fuels up to 10 % of the furnace thermal output at full load, which is 790 MW. In addition to the regular fuels (i.e. coal, coke and petroleum coke), pyrolysis coke and pyrolysis gas can also be used. The coke is first fed into the coal bunkers, ground together with the coal and then blown into the boiler with dust burners.

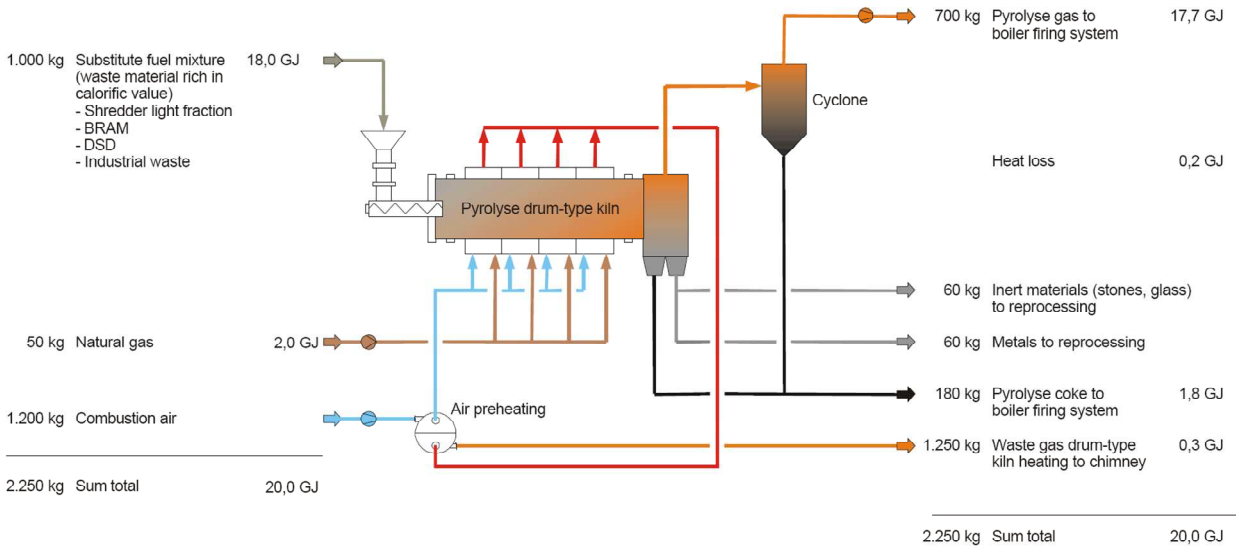

Figure 8. Mass and energy balance of the ConTherm plant (BRAM stands for Brennstoff aus Müll – 70-85 wt% paper and pulp, 10-13 wt% polymers and other components; DSD stands for synthetic granules from the Dual System Germany) (UBA, 2001).

The incineration of the pyrolysis product runs at temperatures of approximately 1600 °C. Due to the high ratio of sulphur to chlorine in the crude flue gas, and because of the cooling to approximately 120 °C, any new formation of dioxins is prevented. All toxic agents that have not been vaporized, are bound into the melting chamber granulate together with the recycled airborne dust and the ground inert material. The mass and energy balance of the ConTherm plant are illustrated in Figure 8.

Depending on the calorific value of RDF (15-30 MJ/m³) it is possible to reduce primary fuel such as coal in the range of 0.5 to 1.0 ton of hard coal per ton of RDF. Emission data are not available.

2.4 Combination processes

Besides the individual processes (incineration, gasification or pyrolysis), combinations of these processes, possibly combined with other processes (e.g. melting, distillation) are also applied. A limited selection of combination processes is presented in the following subsections.

2.4.1 Combination pyrolysis – gasification

Two different types of pyrolysis – gasification combinations are applied, *subsequent processes* and directly connected processes. In the former type, the waste needs to be dried and shredded before being introduced in the first thermal stage. Metals and, if required, inert material may be removed after the pyrolysis step. As pyrolysis gas and pyrolysis coke require reheating during the gasification process, the technical and energetic requirements are higher compared to directly connected processes. The pyrolysis gas is cooled to condense exhaust vapour and pyrolysis oil. At this stage, metals and inert materials can be removed from the pyrolysis coke. The pyrolysis gas is then supplied, together with the pyrolysis oil and the fine solid fraction, to the second thermal stage, which is an entrained flow gasifier. The oil and the fine fraction are gasified in the entrained flow at high pressure and at a temperature of 1300 °C. The resulting synthesis gas is cleaned and then combusted for energy recovery. Solid residues are withdrawn as melted granulates through a water bath. A conversion plant for the treatment of 100 kton per year of MSW and 16 kton per year of dehydrated sewage sludge was approved at Northeim (Germany) (UBA, 2001).

Although *directly connected processes* (see Figure 9) are characterized by improved electricity generation rates, the metals and inert material go into a melt for which no use has been found to date. The un-shredded waste is dried in a push furnace and partially pyrolyzed, whereafter it is transferred directly and without interruption into a packed bed gasifier. In the lower part oxygen is added resulting in gasification at temperatures up to 2000 °C.

Pure oxygen is also added in the upper part of the gasification reactor to destroy the remaining organic components in the generated synthesis gas, through oxidation, gasification and cracking reactions. Although reported to be capable of treating a wider range of wastes (LHV of 6-18 MJ/kg and moisture content below 60 %), this process is mainly used for MSW and non-hazardous industrial wastes. Automotive shredder residues (ASR - Automotive Shredder Residue) with a chlorine content of up to 3.5 % have been treated with approximately equal amounts of MSW (BREF, 2006). The synthesis gas is subjected to a gas cleaning process and then combusted to recover the energy value. The solid residues leave the reactor molten. During test operations, approximately 220 kg of bottom ash was treated with approximately 30 kg metals accumulated per ton of waste input. A plant of this type with a MSW throughput of 108 kton per year is currently under construction at Ansbach (Germany).

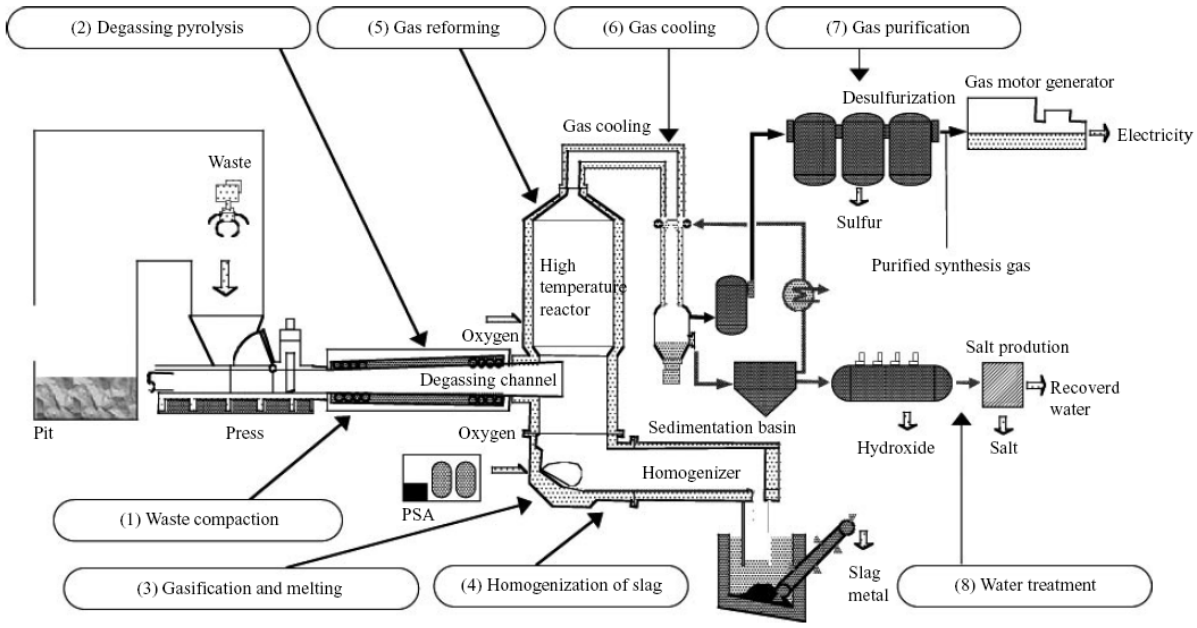

Figure 9. Schematic diagram of pyrolysis – gasification process as operated by Thermoselect (Yamada et al., 2004).

Another plant with a throughput of 225 kton per year has been built at Karlsruhe (Germany), but has not yet achieved the design throughput. Seven plants of this type are running in Japan (Themelis, 2007).

2.4.2 Combination gasification – combustion

Figure 10 shows the combination of a fluidized bed gasifier and high temperature combustor, resulting in ash melting. Shredding residues, waste plastics or shredded MSW are gasified in an internally circulating bubbling fluidized bed, which operates at about 580 °C. Larger inert particles and metals are discharged at the bottom and separated from the bed material. The bed material is returned to the gasifier. Fine ash, small char particles and combustible gas are transferred to the cyclonic ash melting chamber, where air is added to achieve the desired temperature for ash melting (normally 1350-1450 ºC). The ash melting chamber is an integrated part of the steam boiler, used for energy recovery. Products from this process – besides power or steam – are ferrous and non-ferrous recyclable metals, a vitrified slag (low leaching risks and stable) and metal concentrates derived from the secondary ash.

In contrast to other gasification processes, this process is operated at atmospheric pressure and using air rather than oxygen. Pretreatment of MSW by shredding is necessary to reduce particle size to 300 mm diameter. Wastes already within this specification can be treated without shredding. In the various plants in operation, other wastes like sewage sludge, bone meal, clinical waste and industrial slag and sludge are treated in addition to MSW (EBARA, 2003).

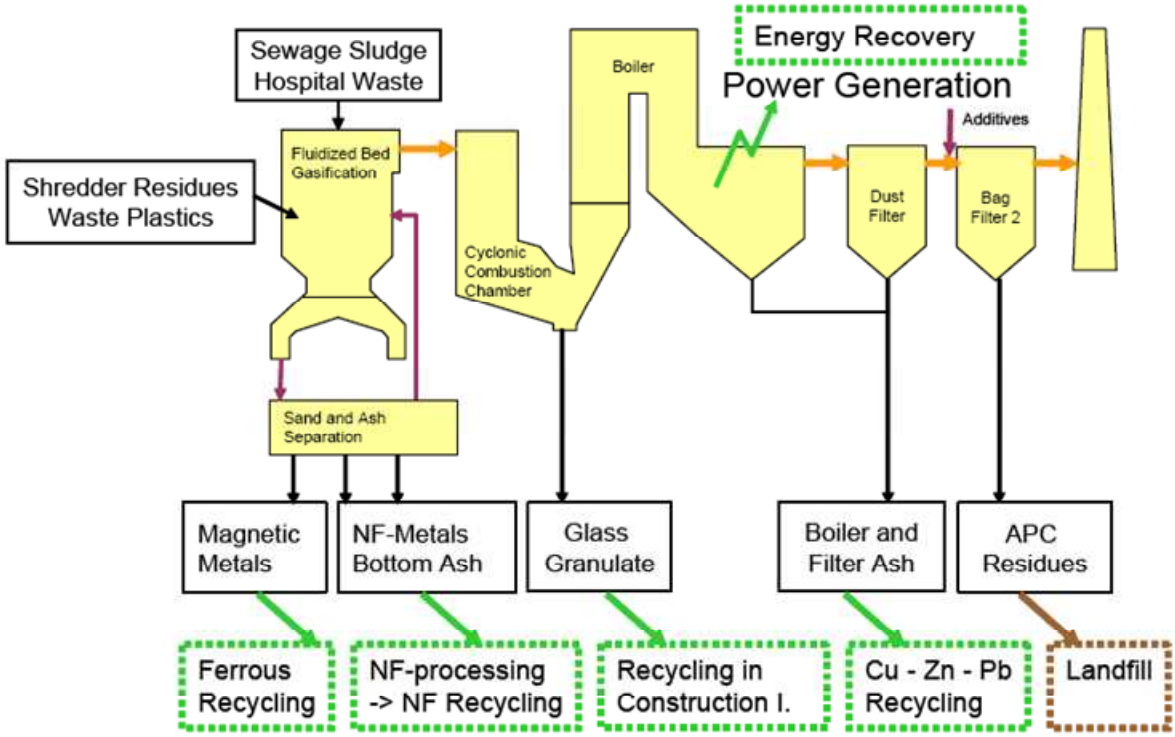

Figure 10. Combined fluidized bed gasification and high temperature combustion process (NF stands for non-ferrous) (EBARA, 2003).

2.4.3 Pyrolytic distillation

Pyrolytic distillation can be seen as the combination of pyrolysis and distillation. Pyrolysis reactions occur in the warm zone at the bottom of a high reactor column. Both temperature and pressure decrease stepwise with the height of the column, similar to what is found in a distillation process. The main difference with conventional pyrolysis is the absence of a liquid product due to the successive cracking, cooling and condensation processes when a vapour is flowing upwards. After condensation on the solid products it moves downwards again, being exposed to higher temperatures and being cracked again. Consequently, pyrolytic distillation results in solid and gaseous products only.

The Chartherm process is a pyrolytic distillation process which aims at maximizing the useful recovery of both materials and energy from waste. The process, developed by the company Thermya (France), is a thermochemical process on industrial scale (capacity of 1500 kg per hour wood waste). The Chartherm process is schematically presented in Figure 11. The complete process can be divided into three sections: crushing, “chartherisation” (thermochemical conversion) and separation (or refining) (Helsen, 2009). This process can be considered as a commercially proven technology for treating wood waste and other organic waste, in particular wood that has been impregnated with heavy metals (e.g. chromated copper arsenate (CCA) wood waste). Conventional gasification and pyrolysis of wood produce a sticky tar fraction which can cause maintenance problems (e.g. fouling of heat exchanger).

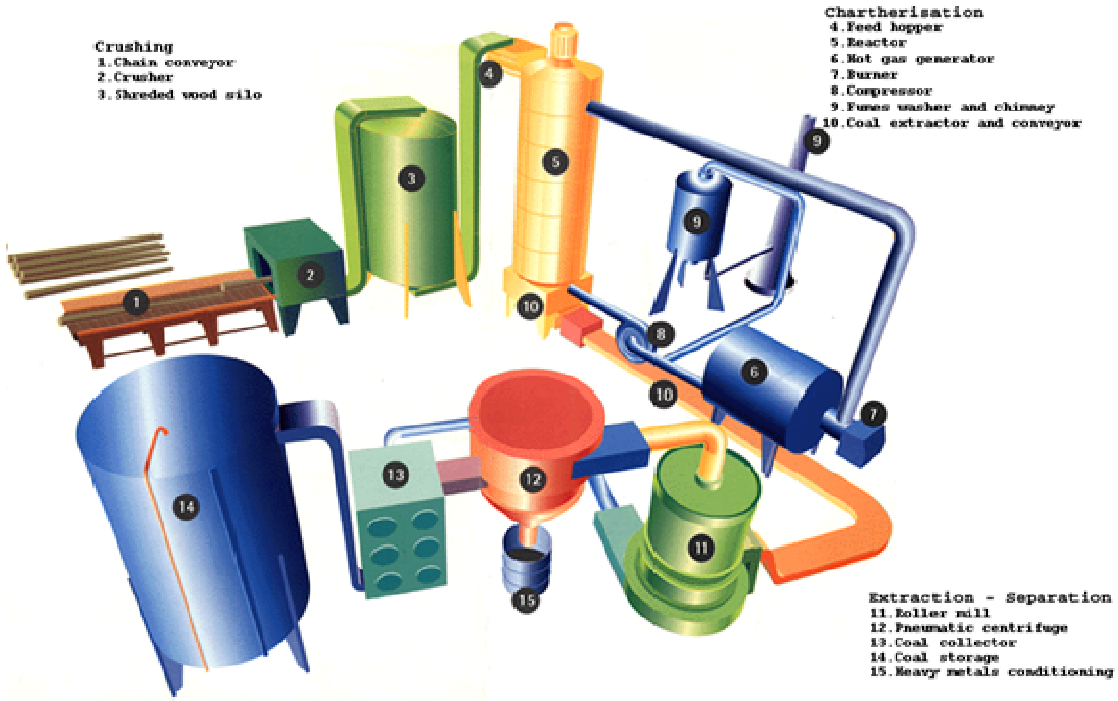

Figure 11. Schematic presentation of the Chartherm process (Helsen et al., 1998).

However, the temperature gradient in the chartherisation reactor breaks down the heavy tar components in favour of lighter volatile components, hence avoiding the tar problem.

The volatile combustible gases, free of metals, leave at the top of the reactor where they are washed by a water scrubber and subsequently burned in a gas burner that supplies energy to the system. The charcoal product is cooled, compressed to powder and fed to the subsequent separation stage. In order to obtain a clean carbon product on the one hand, and a powder containing the metals, minerals and some carbon on the other hand, an appropriate centrifugal separation technique needs to be applied. More detailed information about the Chartherm process for CCA wood waste treatment can be found elsewhere (Helsen, 2009). Other types of solid organic waste have also been fed to the installation but more detailed information has not been supplied.

The pyrolytic distillation process offers the following advantages:

- The operating temperatures (300-400 °C) are relatively low compared to conventional pyrolysis and gasification processes (500-1500 °C). Consequently, energy requirements are also expected to be lower.
- Tar and dioxin emissions are avoided, resulting in reduced gas cleaning equipment.
- It is possible to recover both materials and energy from the waste feed. Separation of the charcoal product results in the recovery of a high calorific carbon product on the one hand, and valuable metals and minerals on the other hand. Furthermore, the pyrolysis gases are burned to supply thermal energy to the reactor.

For the treatment of heterogeneous waste streams with a variable composition (e.g. RDF), the Chartherm process might not be the most appropriate technique. The process requires close monitoring of the process conditions in order to ensure optimal working conditions within the chartherisation reactor. It is relatively straightforward to set the optimal process conditions for a

homogeneous waste input with fixed composition (e.g. wood chips). However, a heterogeneous input with variable composition would require constantly changing process conditions in order to ensure a high process efficiency and elimination of harmful emissions, which is difficult to accomplish. Moreover, the fluctuations in composition of the input waste are likely to be reflected in the quality of the carbon product which strongly reduces its market value.

2.5 Plasma-based technologies

Plasma is known as the fourth state of matter. The presence of charged gaseous species makes the plasma highly reactive and causes it to behave significantly different from other gases, solids or liquids. Plasma is generated when gaseous molecules are forced into high energy collisions with charged electrons, resulting in the generation of charged particles. The energy required to create plasma can be thermal, or carried by either an electric current or electromagnetic radiations.

Depending on the energy source used and the conditions under which the plasma is generated, two main groups of plasmas can be distinguished (Huang and Tang, 2007): the high temperature or fusion plasmas, in which all species are in a thermodynamic equilibrium state and the low temperature plasmas or gas discharges. The low temperature plasmas can further be divided into thermal plasmas in which a quasi-equilibrium state occurs (high electron density and 2,000 °C < Tplasma < 30,000 °C), and the cold plasmas characterized by a non-equilibrium state (Tendero et al., 2006).

Most thermal plasmas are generated by either an electric arc, created by a plasma torch, or by a radio-frequency induction (rfi) discharge. Two types of plasma arc torches exist, the transferred torch and the non-transferred torch (Heberlein, 1992a). The transferred torch creates an electric arc between the tip of the torch and a metal bath or the conductive lining of the reactor wall. In the non-transferred torch configuration, the arc is produced within the torch itself. The plasma gas is fed into the torch, heated, and then exits through the tip of the torch.

The application of plasma-based systems for waste management is a relatively new concept. The principal advantages that plasma offers to waste treatment processes have been summarized by Heberlein (Heberlein, 1992b):

(a) High energy densities and high temperatures, characteristics which allow:

- rapid heating and reactor start-up,
- high heat and reactant transfer rates,
- smaller installation size for a given waste throughput,
- melting of high temperature materials.

(b) Use of electricity as the energy source, resulting in:

- decoupling of the heat generation from the oxygen potential and the mass flow rate of the oxidant or air, increasing process controllability and flexibility,
- lower off-gas flow rates and consequently lower gas cleaning costs,
- the possibility of producing valuable (saleable) co-products.

For the majority of wastes, economic considerations dictate the use of several treatment technologies. Plasma technologies use electricity, an expensive energy vector, turning economic considerations into the strongest barrier for using plasmas for waste treatment. Here, the use of plasmas is attractive when the valuable co-products compensate for the actual costs. Generation of syngas, hydrogen or electricity are prime examples of such co-products.

Plasma technologies for waste treatment can be divided into different categories (Heberlein and Murphy, 2008): plasma pyrolysis, plasma gasification, plasma compaction and vitrification of solid wastes, and combinations of the three already mentioned (in particular for solid wastes with high organic contents). In selecting the optimal waste treatment process, the waste composition is an important parameter. For waste streams that contain high concentrations of organic materials with high heating value, plasma processes can offer an attractive alternative to complete combustion and steam generation as the plasma treatment recovers the energetic content of the waste in the form of a synthesis gas. Waste streams with a high concentration of halogens, including most of the plastic materials, require a very high temperature treatment and quenching in order to prevent or reduce toxic emissions, and to control the product composition. The economics are usually unfavourable since it is more difficult to obtain a valuable (co)product. Waste streams containing inorganic solid materials can be treated for recuperation of valuable components or can be reduced in volume through melting (increasingly being used for hazardous wastes) or can be oxidized and immobilized in a vitrified non-leaching slag.

2.5.1 Plasma pyrolysis

Among the different plasma waste treatment processes, the most extensive scientific studies have been performed on plasma pyrolysis (Heberlein and Murphy, 2008). These studies include computational fluid dynamics (CFD) calculations of the plasma flow in the reaction chamber combined with chemical reaction calculations; more information can be found in the literature (Murphy and Kovitya, 1993; Murphy and McAllister, 1998; Murphy and McAllister, 2001). Different kinds of organic wastes, varying from plastic and used tires to agricultural residue and medical waste, have been subjected to plasma pyrolysis tests in laboratory and pilot-scale projects (Huang and Tang, 2007). Plasma pyrolysis of organic waste usually results in two product streams: a combustible gas and a carbonaceous residue (char). Plasma pyrolysis is an attractive technique for material recovery. Laboratory experiments have shown that plasma pyrolysis offers potential for carbon black recovery from used tires (Tang and Huang, 2005). Hereby, the inorganic components and the carbon black filler are discharged as solid residue relatively unaltered and therefore can theoretically be recycled in carbon black related applications. Although important research progress in this area has been made in recent years, there are still considerable technical challenges to be faced in developing and modifying plasma pyrolysis processes for treating *solid* waste streams, for industrial applications.

However, plasma pyrolysis of hazardous *liquids and gases* is becoming increasingly important and is already a commercially proven technology. The PLASCON process (developed by CSIRO and SRL Plasma Ltd. in Australia, and now owned by DoloMatrix International Ltd.) uses plasma pyrolysis to treat fluid wastes containing halogenated hydrocarbons, CFCs, HFCs, PCBs and other harmful components. The process uses a direct current (DC) plasma torch with tungsten cathode and argon as plasma gas. Presently, ten plants are operating in Australia, Japan, USA and Mexico (Heberlein and Murphy, 2008).

In this review, the focus is on treatment of solid wastes, MSW and RDF in particular. For this type of waste streams, plasma pyrolysis is often combined with gasification in order to generate a synthesis gas with higher heating value while reducing the energy consumed by the plasma torches to gasify the waste (Do and Leatherman, 2006). This is explained by the exothermic nature of the gasification reactions taking place. The introduction of a controlled amount of air, O_2 and/or O_2-enriched air into the reaction zone promotes the following reactions:

$$(1)\ C_xH_y + {}^{x}/_{2}\,O_2 = x\,CO + {}^{x}/_{2}\,H_2$$

$$(2)\ 2\,C + O_2 = 2\,CO$$

$$(3)\ C + H_2O = CO + H_2$$

The oxidative reactions (1) and (2) are exothermic, reaction (3) is endothermic in nature. The controlled input of O_2-enriched air supplies enough oxygen to initiate the oxidative reactions (1) and (2), but not enough to promote the complete oxidative combustion reaction (4). As a result, the energetic efficiency increases.

$$(4)\ C_xH_y + (x + {}^{y}/_{4})\,O_2 = x\,CO_2 + {}^{y}/_{2}\,H_2O$$

There exist relatively small scale plasma pyrolysis installations for treating polymers (Guddeti et al., 2000), medical waste (Nema and Ganeshprasad, 2002) and low-level radioactive waste (HTTC, 2009). However, no information was found on industrial plasma pyrolysis installations processing MSW or RDF. Plasma gasification and vitrification, a technology being discussed in the next subsection, seems to be preferred over plasma pyrolysis for this type of waste streams. For this reason, plasma pyrolysis is not discussed in more detail here.

2.5.2 Plasma gasification and vitrification

Although gasifiers such as fluidized bed systems have existed for many years, the energy contained in a plasma allows the use of low-energy fuels, such as household and industrial waste that often cannot sustain their own gasification without additional fuel. For this reason, there is an increasing interest in plasma gasification, an innovative technology for converting waste streams into a valuable synthesis gas and a vitrified slag by means of thermal plasma.

The high temperature conditions that are reached in plasma gasification result in the decomposition of organic compounds into their elemental constituents, forming a high-energy synthesis gas, consisting mainly of hydrogen and carbon monoxide. On the one hand, tar, char and dioxins are broken down, resulting in a synthesis gas that is cleaner compared to conventional gasification processes. The inorganic fraction (glass, metals, silicates, heavy metals) on the other hand, is melted and converted into a dense, inert, non-leaching vitrified slag. The synthesis gas can be used for efficient production of electricity and/or heat, or second generation liquid (bio)fuels (e.g. Fischer Tropsch diesel) (Malkow, 2004). The vitrified slag should be inert for leaching processes and consequently applicable as, for example, a building material additive (Lapa et al., 2002).

The synthesis gas produced in the plasma gasification process contains the plasma gas components. *Air* is used most frequently, for economic reasons and for providing oxygen for reactions with organic components. In some applications it can be advantageous to use *oxygen* as plasma gas as this reduces the total gas flow in the reactor as well as the nitrogen amount (Heberlein and Murphy, 2008). Plasma torches operating with *nitrogen* and *carbon dioxide* provide higher arc voltages, increasing the jet power. A similar effect can be obtained with *steam* plasmas. R&D activities at the Czech Academy of Sciences (Hrabovsky, 2002) and at the Tokyo Institute of Technology (Watanabe and Shimbara, 2003), have shown that plasma torches operating with steam offer definite advantages for waste processing applications. However, it should be noted that the mixture of hydrogen, oxygen and hydroxide radicals leads to strong electrode erosion. *Argon* can

also be used as plasma gas. It offers long electrode life, but the low specific heat of argon results in relatively low torch power levels and enthalpy fluxes of the gases leaving the torch. Moreover, reactive species such as oxygen atoms are generated only indirectly through energy transfer from argon to oxygen which leads to low energy transfer rates due to the relatively low thermal conductivity of argon (Heberlein and Murphy, 2008).

The fact that gas plasma technologies for waste treatment use electricity as energy source instead of the energy content of the treated substances, makes the system very flexible and controllable. The plasma torch is an independent heat source, which allows controlling the process temperature independently from fluctuations in feed quality and supply of air/oxygen/steam required to gasify the feed (Lemmens et al., 2007). Therefore, variable waste inputs do not pose problems. Among the different plasma processes, thermal arc plasmas dominate in waste treatment because they are relatively insensitive to changes in process conditions. Furthermore, solid waste treatment often requires decontamination in combination with volume reduction and immobilisation of inorganic contaminants. Therefore, most plasma-based waste treatment systems make use of transferred arc reactors offering high heat fluxes, advantageous for solids melting (Heberlein and Murphy, 2008).

Westinghouse (Madison, USA) and Europlasma (Morcenx, France) pursue a different approach; their design includes a non-transferred plasma torch to provide part of the heat required for waste processing, while the remainder of the process energy is provided by the heating value of the waste or by the addition of coke. The *Westinghouse* plasma reactor (shown in Figure 12) is a plasma fired furnace containing the waste and coke (about 4 wt% of the total load). Plasma heating of a fraction of the air reduces the amount of coke and air needed to generate the high temperatures in the furnace. The waste composition determines how much of the incoming air needs to be plasma heated. More detailed information about the Westinghouse process and its implementation can be found in (Juniper, 2008; WPC, 2010). *Europlasma* uses plasma reactors with non-transferred arc torches for incinerator residue compaction, the waste is heated directly with plasma jets. The plasma direct melting reactor installed in Cenon (France) processes up to 10 ton/day of fly ash, a larger installation in Shimonoseki (Japan) can process 42 ton/day of fly ash and bottom ash. Europlasma plans to build, in 2011, a 12 MW gasification plant for solid waste treatment in Morcenx (France) (Europlasma, 2008). The design includes two plasma torches, a first one to refine the raw synthesis gas produced during gasification, and a second one to vitrify metals and minerals. It is not clear, however, to which extent the plasma treatment (patented under the name TurboPlasma) replaces the different synthesis gas cleaning stages.

A fundamentally different type of plasma arc waste conversion uses plasma to refine gases produced during waste conversion (two-stage process) rather than to destroy waste by brute force as occurs in the above-mentioned plasma systems (single-stage). *Plasco Energy Group* completed a plasma-arc waste demonstration plant in Ottawa (Canada) to process 85 ton/day of MSW. Plasco uses plasma only to refine the gases released from the gasification of the waste in an oxygen-starved conversion chamber. With the torches interacting only with the gas, there is limited electricity demand. In the process, waste is converted into a syngas that is used to run internal combustion gas engines (ADEME, 2009).

The Gasplasma™ process commercialized by *Advanced Plasma Power* (APP, Swindon, United Kingdom) combines fluidized bed gasification with plasma cleaning of the resulting hydrogen-rich syngas. Figure 13 shows the Gasplasma™ system flow sheet.

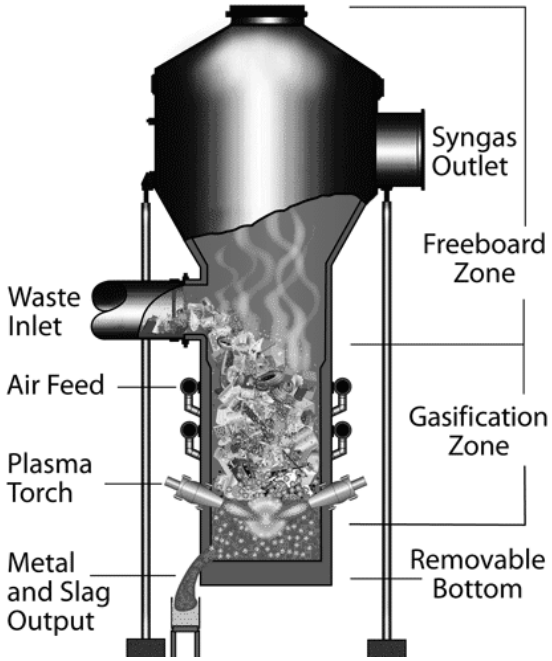

Figure 12. Alter NRG/Westinghouse plasma gasification reactor (WPC, 2010).

The syngas production process comprises two steps; first, in a fluidized bed gasifier VOCs and carbon are converted into a crude syngas using a fraction of the thermal energy in the waste and next, a plasma converter provides the high temperature environment for converting residual tars and chars, allowing vitrification of the ash into a non-leaching slag. According to the Fichtner validation report (Fichtner, 2008), the Gasplasma™ process has shown to be capable of producing a synthesis gas which, after passing through further gas treatment, is suitable for use as a fuel in a gas engine. Rigorous pilot plant trials performed on RDF from a different number of sources, justify this statement. More detailed information on the Gasplasma™ process can be found in (Fichtner, 2008; APP, 2010).

The purpose of developing a two-stage gasification process (with plasma gas cleaning) was to overcome some drawbacks related to the process combining gasification and plasma conversion in one reactor. The latter has a relatively low throughput, poor control of VOCs/tars and a low conversion efficiency to a valuable syngas (i.e. a clean and high calorific syngas). These parameters relate to the interaction of the waste feed (RDF) with the plasma system. The reduced throughput relates to the fact that plasma decomposition of RDF is much slower than the decomposition of tars and chars in the syngas. Single-stage plasma gasification processes consume approximately 800 kWh electricity per ton of MSW, corresponding to approximately 2,000 kWh of primary energy (assuming an average efficiency of 40 % for electricity generation) which is close to the total energy contained in one ton of MSW (i.e. 2,500 kWh). Such high energy consumptions can only be justified in case of wastes that cannot be processed in another way (e.g. asbestos-containing). Therefore, the single-stage gasification process seems to be the better choice when dealing with small process streams (e.g. hazardous or medical waste), while the two-stage gasification process performs better for larger waste streams (Taylor, 2009).

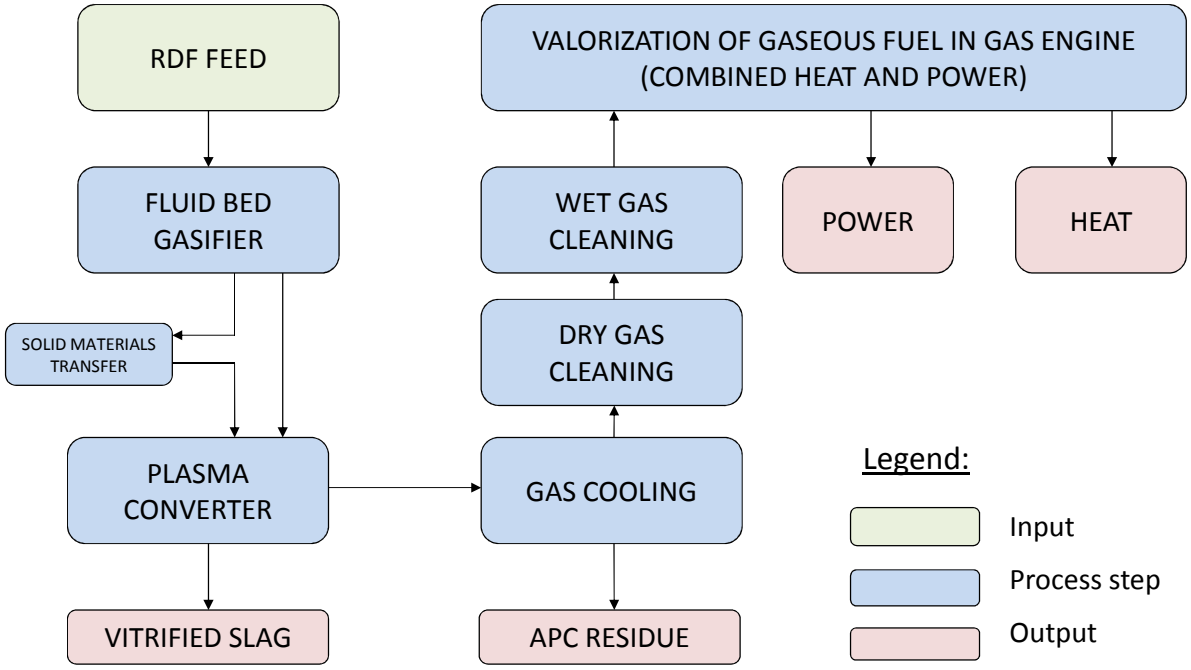

Figure 13. Flow sheet of the Gasplasma™ process (based on online information provided by Advanced Plasma Power (APP, 2010).

Table 3 lists specific electricity requirements (net electric power consumed per ton waste) for a number of plasma gasification waste treatment processes (Heberlein and Murphy, 2008). It is clear that published results cover a wide range of electricity requirements. This is caused by differences in plant dimensions (pilot versus full scale), waste input, operating conditions, etc.

Modern incinerators consume less electricity per ton waste processed (typically around 130 kWh per ton (Cleiren and GOM-Antwerpen, 2000; Vanderreydt, 2010)) than plasma based systems. Electricity consumption is however not the only economic consideration in waste treatment. Plasma systems show potential for higher net electrical efficiencies than waste incinerators since gas engines generate electricity more efficiently than steam turbines. Other parameters in favour of plasma technologies include the avoidance of landfill cost, the added value of reusable vitrified slag and, in the long-term perspective, the development of a more sustainable waste management practice.

It was mentioned earlier that process efficiencies can be increased by using plasma heat as an auxiliary source of energy, e.g. in the Plasco process and the Gasplasma™ process. The economic feasibility study of plasma arc gasification conducted on behalf of the City of Marion, Iowa, USA (Clark and Rogoff, 2010) states that the net electricity production for plasma processes equals, on average, 450-550 kWh per ton. Furthermore, it is mentioned that independent third party sources have determined that net power outputs for plasma processes can be significantly lower, depending on the plasma technology and plant configuration. The same study indicates a net electrical efficiency of 24 % for the Plasco process. This corresponds to a net electricity production of 600 kWh per ton. On the other hand, an expertise assessment of the Plasco gasification process for MSW treatment (ADEME, 2009) reports an electrical efficiency of only 19 % due to operational and design issues resulting in low plant availability.

Table 3 - Electric power requirements for plasma gasification processes (Heberlein and Murphy, 2008).

Plasma gasification technology	Feedstock	Electric power requirement [kWh/ton]
Westinghouse Plasma Corp. (Japan)	MSW + ASR	100-250
Europlasma (France, Japan)	Fly ash	800-1,300
Tetronics (United Kingdom)	Bottom ash	550
Integrated Environmental Technologies (USA)-Pyrogenesis Corporation (Canada)	Medical waste-MSW	1,100-845

Literature reviews on plasma technologies for waste conversion are limited. Literature data is often restricted to lab-scale or pilot-scale installations, and only rarely covers full-scale facilities since they are not yet widely spread. In Japan, however, several commercially-proven plasma gasification facilities for waste treatment can be found, e.g. in Utashinai and in Mihama-Mikata, processing respectively 180 and 22 ton per day. These two plants make use of the Westinghouse plasma gasification process which has been critically reviewed by Juniper Consultancy Services Ltd. (Juniper, 2008).

3. CONCLUSIONS

Waste management has evolved to a stronger focus on material recuperation and recycling (e.g. glass, paper, etc.), and waste prevention. However – despite increasing attention for waste prevention and sustainability – total MSW generation in the EU25 is forecasted to continu to rise over the next decade (ETC/RWM, 2007). Waste-to-Energy (WtE) technologies are of essential importance in the development of a more sustainable waste management practice. This paper reviews thermochemical conversion technologies for the energetic valorization of calorific solid waste streams. Although some WtE processes accept raw (i.e. as received) MSW as input, the majority of WtE processes require a preprocessed form of MSW in order to avoid variable and/or unstable operating conditions as well as fluctuating product qualities. This is schematically represented in Figure 14. Roughly, two types of MSW pretreatment can be identified: shredding – the main goal is size reduction, and conversion into RDF – the main goals are homogenization of physical and chemical properties as well as increasing the energy density of the waste. Additional benefits of converting MSW to RDF are lower pollutant emissions, reduced excess air requirement during combustion and finally, easier storage, handling and transportation. As is shown in Figure 14, the same type of WtE techniques are applicable to both shredded MSW and RDF. However, it should be pointed out that product qualities (e.g. vitrified slag – substitute for building aggregates, synthesis gas – production of electricity, chemicals) might differ significantly. The more homogeneous properties of RDF allow for tighter process control, thus more stringent product quality specifications can be met.

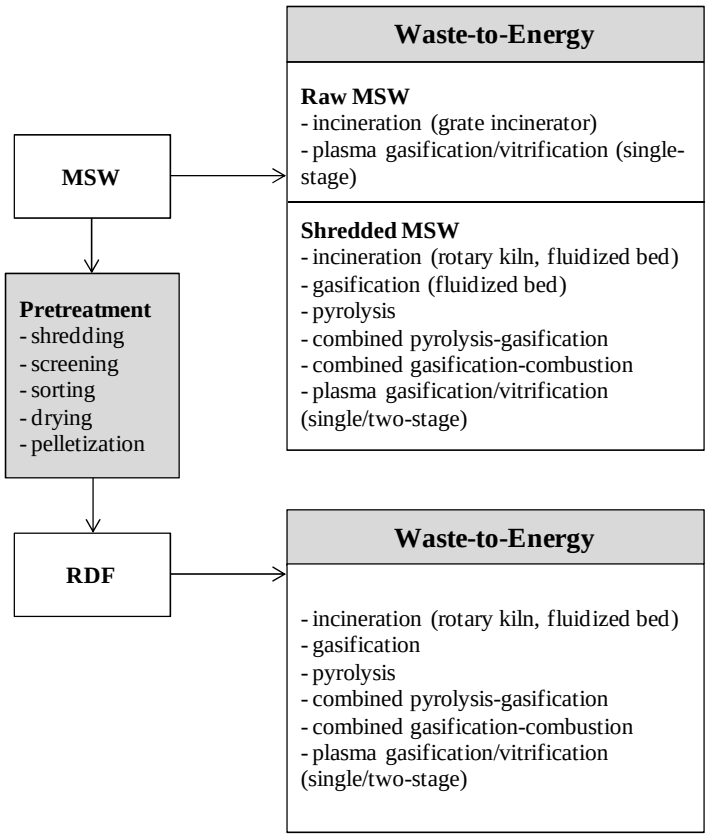

Figure 14. Comparison of thermochemical WtE technologies for MSW and RDF.

Figures 15 to 18 show the simplified process schematic for the four main types of thermochemical treatment technologies for calorific solid waste that have been discussed in this paper (incineration, pyrolysis, gasification and plasma gasification/vitrification, respectively). The advantages and disadvantages offered by these technologies for MSW and/or RDF treatment, in addition to the possibilities they offer in view of the WtE and WtP concept are discussed in more detail below.

Treatment of waste streams is subjected to increasingly strict legislation. Furthermore, conventional technologies, such as *incineration*, have their limitations, among them the production of residual waste products, both solid (highly leachable fly ash and bottom ash) and gaseous (NO_x formation and incomplete destruction of halogenated hydrocarbons). By applying flue gas cleaning and conditioning processes some pollutants are shifted from the gaseous to the liquid or solid phase, nevertheless a residual waste stream remains. Although significant waste volume reduction is obtained, still a substantial volume of residues has to be disposed of – mostly on landfills. Fly ash requires immobilization to make it environmentally safe for landfill disposal. Moreover, bottom ash from MSW incineration usually contains dioxins, halogenated hydrocarbons and heavy metals, thus it might be classified as hazardous in the future. This might call for supplementary vitrification units which require substantial additional energy, resulting in less potential for energy recovery. As is shown in Figure 15, the WtE possibilities for MSW incineration consist of recovering heat directly from the process and/or generating electricity using steam turbines. Incineration is the full oxidative combustion of the organic fraction of waste, hence the flue gas consists mainly of CO_2 and H_2O.

Consequently, the gas quality does not comply with the high-quality standards required for gas turbines and gas engines which produce electricity more efficiently than steam turbines.

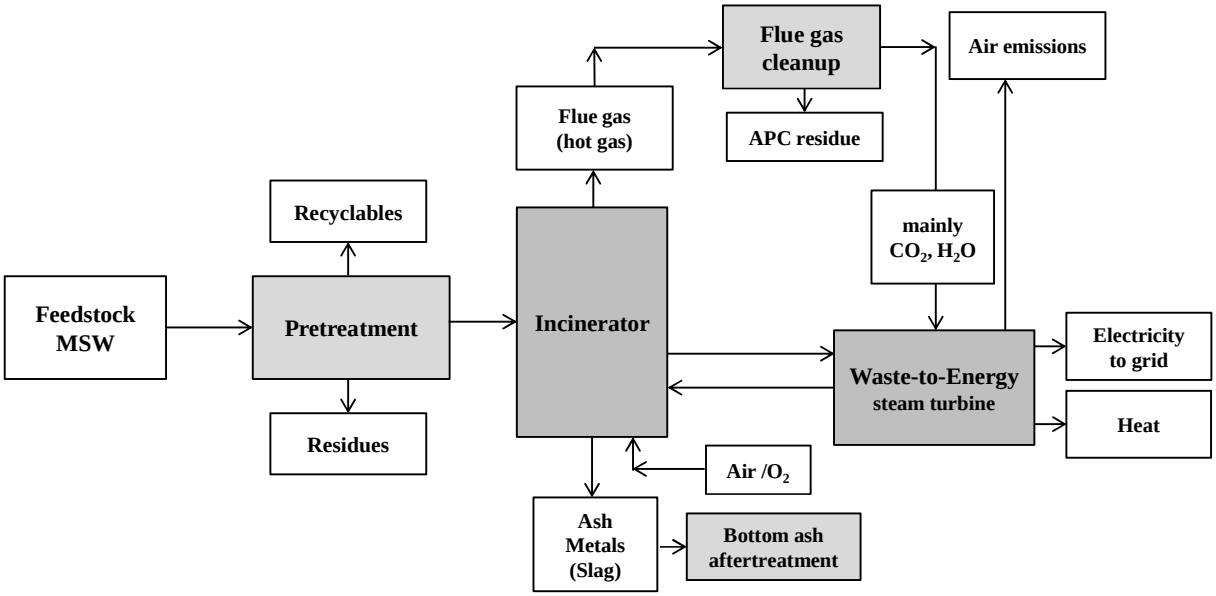

Figure 15. WtE – from MSW to electricity through incineration (APC stands for Air Pollution Control).

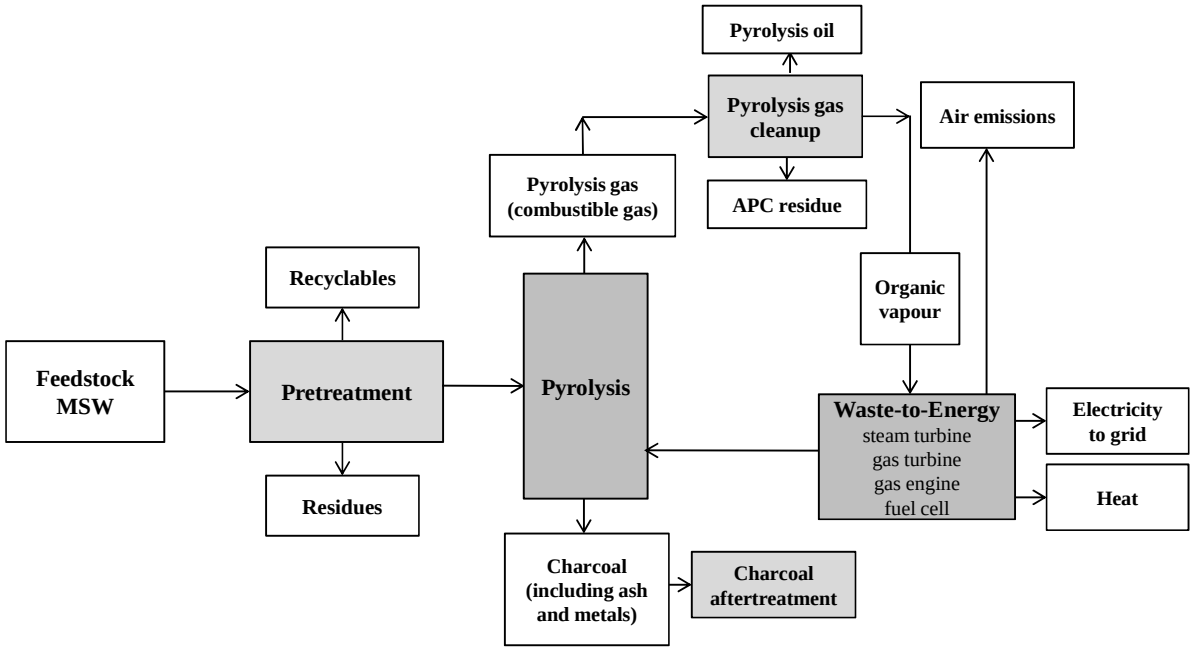

Figure 16. WtE – from MSW to electricity through pyrolysis.

Pyrolysis is the thermochemical decomposition of organic material in the absence of oxygen, thereby producing a combustible gas, a solid product and – depending on the type of pyrolysis process – a liquid product.

As is shown in Figure 16, the gaseous stream consists primarily of CO and H_2, which makes it suitable for combustion in gas turbines and gas engines, and even for use in fuel cells.

A number of *pyrolysis* projects exist in Europe and elsewhere (notably in Japan) receiving certain specific types or fractions of waste, often after pretreatment.

Pretreatment/ aftertreatment is recognized as an essential step in waste pyrolysis. Process conditions need to be optimized with respect to the specific waste input considered. The process viability is highly dependent on the presence of potential pollutants, which could make the pyrolysis products useless, or at least difficult to use, without additional treatment step(s).

For this reason, the usefulness of pyrolysis (without any additional pretreatment of the waste input or aftertreatment of the pyrolysis products) for secondary fuel production or substance recovery from waste might be questioned for some types of waste. When used for MSW management, the fact that the ash from the pyrolysis process is usually disposed of in a landfill constitutes one of the major environmental shortcomings of the pyrolysis process (Young, 2010).

Gasification has several advantages over traditional combustion of MSW. It requires only a fraction of the stoichiometric amount of oxygen necessary for combustion. As a result, the formation of dioxins, SO_x and NO_x is limited and the volume of process gas is low, requiring smaller and less expensive gas cleaning equipment. Flue gas volumes in waste incineration range between 5,000 and 6,000 Nm^3 (dry) per ton of waste processed (EMIS, 2010). Advanced Plasma Power claims their plasma gasification technology (Gasplasma™) produces 1,400 Nm^3 crude synthesis gas (dry) per ton of waste processed. The lower gas volume also results in a higher partial pressure of contaminants in the off-gas, which favours more complete adsorption/absorption and particulate capture. The ash residue from MSW gasification requires aftertreatment before it can be sent to landfill. However, certain types of gasification reactors are capable of capturing the ash in a vitrified non-leaching slag (e.g. the high temperature slagging gasifier (EBARA, 2003) and the plasma gasifier (WPC, 2010)). Moreover, waste volume reduction is increased compared to incineration. Manufacturers of plasma gasification systems claim a volume reduction of 99 % as opposed to a 80-90 % volume reduction achieved in combustion. Finally, gasification generates a combustible gas that can be integrated with combined cycle turbines, gas engines and, potentially, with fuel cells for electricity (and heat) generation, these components produce electricity more efficiently than steam turbines. The WtE process schematic for MSW gasification is illustrated in Figure 17.

For these reasons, *plasma technologies* are becoming more and more attractive (Van Oost et al., 2006). In reviewing the applications of plasma technologies to treat calorific solid wastes, it is clear there have been continued improvements towards the development of plasma processes that prioritize environmental quality at affordable cost. The investigation of published results from waste processing facilities using plasmas, indicate that plasma technologies are a promising alternative to conventional thermal treatment processes such as incineration. Refuse derived fuel can be converted into a high calorific syngas which can be used for electricity generation. Moreover, the inorganic fraction of the waste is converted into a vitrified non-leaching slag, this co-product can be used in the manufacture of architectural tiles and construction materials.

Plasma technologies for waste treatment can be divided into different categories; plasma pyrolysis, plasma gasification, and plasma compaction and vitrification.

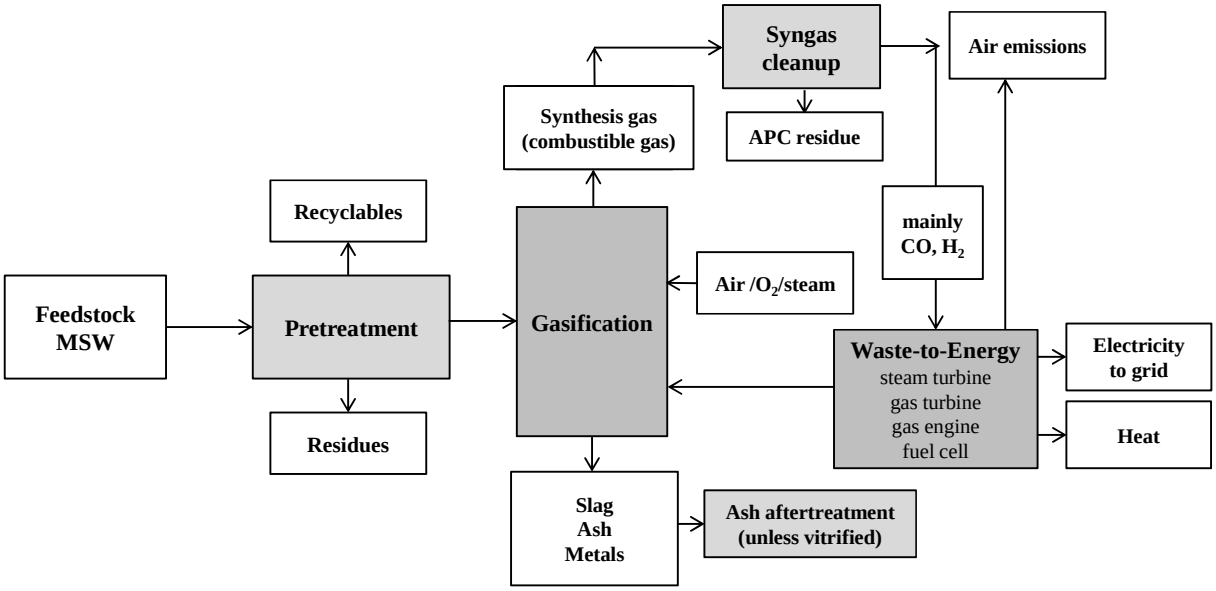

Figure 17. WtE – from MSW to electricity through gasification.

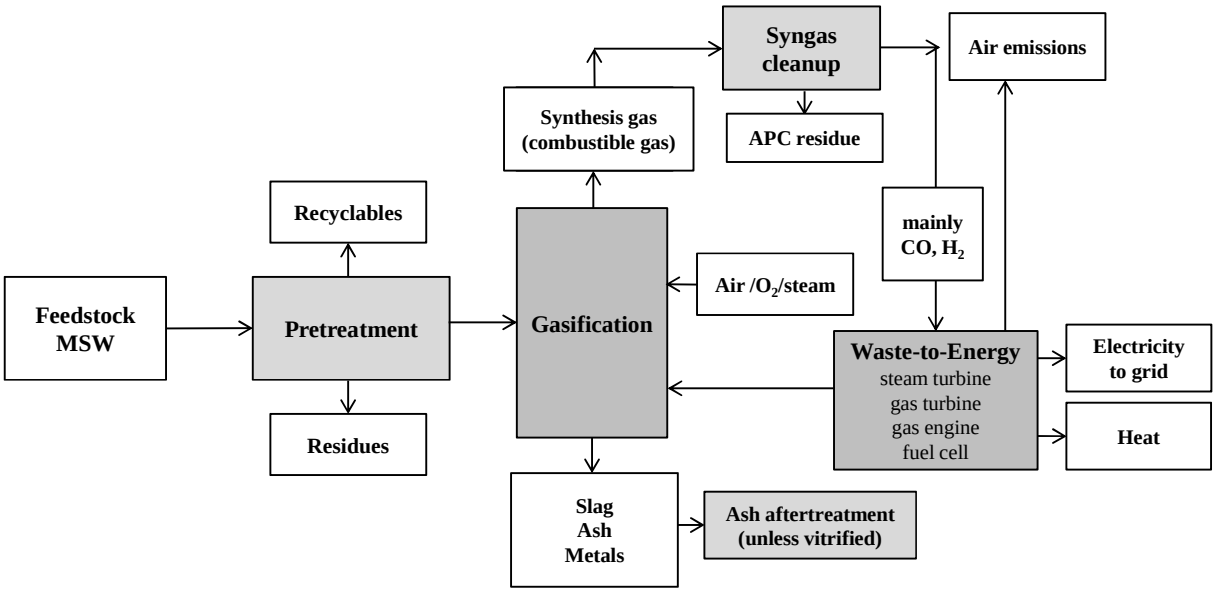

Figure 18. WtE and WtP – from MSW to electricity and other valuable coproducts through plasma gasification/vitrification.

The latter is often combined with plasma pyrolysis or gasification, especially for solid waste containing high fractions of organics. *Plasma pyrolysis* is a proven technology for the treatment of hazardous liquids and gases, in relatively small scale applications.

The Plascon process, for example, is designed to treat approximately 2.4 ton/day (Heberlein and Murphy, 2008). No information was found on plasma pyrolysis installations, pilot-scale or full-

scale, for processing MSW and/or RDF. *Plasma gasification* has been demonstrated as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization (Minutillo et al., 2009). Both single-stage and two-stage plasma gasification systems exist. In the single-stage design the waste is treated directly with plasma jets, while in the two-stage design, gasification is followed by plasma cleaning of the produced synthesis gas. The purpose of developing a two-stage gasification process was to overcome some drawbacks related to the process combining gasification and plasma conversion in one reactor. The single-stage system has a relatively low throughput, poor control of VOCs/tars and a low conversion efficiency to a valuable synthesis gas.

The high process temperatures reached in plasma gasification allow to vaporize volatile metals in their metallic form, and carry them out of the unit, together with halogens and other acid gases, in the off-gas stream. The gas cleaning unit must be designed to separate, collect and/or chemically treat the materials entrained in the off-gas. Operation failure of this cleaning unit may have dramatic consequences, therefore it should be carefully implemented. A wide range of gas abatement techniques are available for this remedial treatment. Residues from the synthesis gas cleaning processes (fly ash, precipitated metals, etc.) can be internally recycled and captured in the slag, which is vitrified and as such shows no leaching risks. During the review of the process characteristics of the four main thermochemical treatment options, it became clear that incineration, pyrolysis and conventional gasification produce ash as by-product, which needs to be disposed of in a landfill. Plasma gasification, on the other hand, is more environmentally friendly since it produces a non-leaching vitrified slag, which can be used to produce other by-products (ceramic tiles, roof tiles, insulating foam, …) or recycled as a road aggregate material (Waste-to-Product). Even hazardous wastes can be converterd into valuable products through plasma vitrification. Europlasma constructed a treatment facility in Morcenx (France) for the destruction of asbestos waste, the vitrified product (labeled as “Cofalit”) is sold for use as a road aggregate or other construction applications (Young, 2010).

Plasma vitrification of fly and bottom ashes generated by incineration of MSW is a proven technology in Japan. Persistent organic pollutants such as dioxins and furans are destroyed and the ash is reduced to a vitrified slag that also captures a significant amount of heavy metal pollutants (e.g. lead, zinc and cadmium). The solid vitrified product is highly resistant to leaching, mechanically strong and environmentally stable. Japan uses 75 % of the vitrified product as a road construction material (Young, 2010). Furthermore, a process has been developed to produce high-value glass ceramic tiles which have potential to replace quality building materials such as granite and marble. Further process development is required in order to commercialize the use of vitrified slag from plasma processes as a high-quality building material. Figure 18 shows the opportunities offered by plasma gasification/vitrification of MSW in the field of WtE and WtP.

The barriers to vitrified slag utilization are mainly institutional, regulatory and legal. In order to overcome these barriers, it needs to be demonstrated that the uses are technically safe, environmentally sound, socially beneficial and commercially competitive. This calls for the development of improved specifications, fact sheets and testing procedures through collaboration of the government, university researchers and standard-setting organizations (Young, 2010).

Although the technical feasibility of plasma waste treatment has been proven for several types of wastes (e.g. hazardous waste, medical waste, RDF), the commercial viability still remains the main issue. Plasma technologies use electricity as heat source rather than thermal energy liberated from combustion, which makes the heat source independent of the treated substances. This provides system flexibility, fast process control and more options in process chemistry, including the

possibility of generating valuable (co)products (Van Oost et al., 2006). However, electricity is an expensive energy form, hence the specific energy consumption of plasma processes should be kept as low as possible. Two-stage plasma gasification in which plasma is used solely to refine the crude syngas coming from waste gasification, has shown to be less energy consuming than single-stage processes in which plasma jets interact directly with the waste. In combination with the avoidance of landfill charges, the added value of the reusable vitrified slag and the electricity and/or heat production from syngas, combined plasma gasification and vitrification offers a promising perspective for sustainable waste treatment.

Only a limited amount of data (concerning emissions, energetic performance, investment and operating costs, technical lifetime, etc.) is available from the literature or system developers. Moreover these limited data often refer to different plant specifications (e.g. to meet different emission standards, water treatment requirements ...) or to different waste inputs. Consequently, it is difficult to quantitatively compare plasma technologies with more conventional technologies for waste treatment, such as incineration. However, the data which have been published show that plasma technologies offer great potential for energetic valorization of calorific solid waste streams.

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List of acronyms

APC	air pollution control
ASR	automotive shredder residue
CCA	chromate copper arsenate
CHP	combined heat and power
CFC	chlorofluorocarbon
CFD	computational fluid dynamics
DC	direct current
EU25	group of 25 countries belonging to the European Union
HFC	hydrofluorocarbon
HHV	higher heating value
HR	heating rate
LHV	lower heating value
MHV	medium heating value
MSW	municipal solid waste
PCB	polychlorinated biphenyls
PCDD/F	polychlorinated dibenzodioxin and dibenzofuran
RDF	refuse derived fuel
RFI	radio-frequency induction

RT	residence time
VOC	volatile organic compound
WtE	waste-to-energy
WtP	waste-to-product

REFERENCES

ADEME (2009) Technical, environmental and economic assessment of PlascoEnergy Group gasification process using plasma torches. Etude réalisée pour le compte de l'ADEME (French Environment and Energy Management Agency) par ENVALYS.

APP (2010) Advanced Plasma Power (APP). What is Gasplasma? – The process. Retrieved 29 March, 2010, from http://www.advancedplasmapower.com/.

BIC (2010) BIC Group - Moving grate incinerator. Retrieved 19 August, 2010, from http://www.bicgroup.com.sg/.

BREF (2006) Reference document on the best available techniques for waste incineration. European Commission, from http://eippcb.jrc.es/reference/wi.html.

BREF (2010) Reference document on best available techniques in the cement, lime and magnesium oxide manufacturing industries. European Commission, from http://eippcb.jrc.es/reference/cl.html.

Bridgewater, A. V. (2003) Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal 91: 87-102.

Bridgwater, A. V. (1994) Catalysis in thermal biomass conversion. Applied Catalysis A: General 116(1-2): 5-47.

Bridgwater, A. V. (1995) Thermal biomass conversion technologies. Biomass and renewable energy seminar, March 1995 1995, Loughborough University, IK.

Bridgwater, A. V. and Bridge, S. A. (1991) A review of biomass pyrolysis and pyrolysis technologies. Biomass pyrolysis liquids upgrading and utilisation. Bridgwater A. V. and Grassi G. London, Elsevier Apllied Science: 11-92.

Clark, P. J. and Rogoff, M. J. (2010) Economic feasibility of a plasma arc gasification plant, City of Marion, Iowa. 18th Annual North American Waste-to-Energy Conference, 11-13 May 2010, Orlando, Florida (USA).

Cleiren, D. and GOM-Antwerpen (2000) Objectieve keuze inzake verwerkingstechnieken. Het objectiveren van de techniekkeuze voor de eindverwijdering van huishoudelijk afval: het praktijkvoorbeeld binnen de provincie Antwerpen. 20ste Internationaal Seminarie – Het Beheer van Afvalstoffen, 11-12 mei 2000, Vrije Universiteit Brussel in samenwerking met RDC.

Do, R. T. and Leatherman, G. L. (2006) Plasma pyrolysis, gasification and vitrification of organic material. United States, Solena Group, Inc. (Washington, DC, USA). U.S. Patent 6,987,792.

EBARA (2003) EBARA. EUP - EBARA UBE Process for gasification of waste plastics. Retrieved May, 2010, from http://www.ebara.ch/.

EMIS (2010) Vlaamse Instelling voor Technologisch Onderzoek (VITO). Energie- & milieu-informatiesysteem voor het Vlaams Gewest. Retrieved 27 July, 2010, from http://www.emis.vito.be/.

ETC/RWM (2007) Environmental outlooks: Municipal waste. Working Paper n° 1/2007, European Topic Centre on Resource and Waste Management, from http://waste.eionet.europa.eu/publications.

Europlasma (2008) Projet CHO-Power – Morcenx. Production d'électricité par gazéification - Energies renouvelables et développement durable.

Fichtner (2008) Advanced Plasma Power – Gas plasma – Stage 5: Assessment report. Cheshire (United Kingdom), Fichtner Engineering and Consulting Services.

GL (2009) Germanischer Lloyd (GL). BGL Gasifier. Retrieved 19 August, 2010, from http://www.gl-group.com/.

Guddeti, R. R., Knight, R. and Grossmann, E. D. (2000) Depolymerization of polyethylene using induction-coupled plasma technology. Plasma Chemistry and Plasma Processing 20(1): 37-64.

Heberlein, J. (1992a) Generation of thermal and pseudo-thermal plasmas. Pure and applied chemistry 64(5): 629-636.

Heberlein, J. (1992b) Thermal plasma for the destruction of hazardous wastes. Plasma Technologies for Hazardous Waste Destruction 1992b, Como (Italy), Editrice Compositori, Bologna (Italy).

Heberlein, J. and Murphy, A. B. (2008) Thermal plasma waste treatment. Journal of Physics D: Applied Physics 41(5): 053001.

Helsen, L. (2000) Low-temperature pyrolysis of CCA treated wood waste. Heverlee (Belgium), K.U. Leuven. PhD.

Helsen, L. (2009) The Chartherm process, what's in the name? Waste Management 29(5): 1649-1657.

Helsen, L., Van den Bulck, E. and Hery, J. S. (1998) Total recycling of CCA treated wood waste by low-temperature pyrolysis. Waste Management 18(6-8): 571-578.

Hrabovsky, M. (2002) Generation of thermal plasmas in liquid-stabilized and hybrid DC-arc torches. Pure and applied chemistry 74(3): 429-433.

HTTC (2009) High Temperature Technologies Corp. (HTTC). Plasma furnace for the treatment and disposal of solid toxic and low-level radioactive waste. Retrieved 15 January, 2010, from http://www.httcanada.com/chemtoxrad.html.

Huang, H. and Tang, L. (2007) Treatment of organic waste using thermal plasma pyrolysis technology. Energy Conversion and Management 48(4): 1331-1337.

Juniper (2008) Alter NRG/Westinghouse plasma gasification review. Stancombe (United Kingdom), Juniper Consultancy Services Limited.

Kaltschmitt, M. and Reinhardt, G., Eds. (1997) Nachwachsende Energieträger - Grundlagen, Verfahren, ökologische Bilanzierung. Braunschweig/Wiesbaden, Vieweg Verlagsgesellschaft.

Kolb, T. and Seifert, H. (2002) Thermal waste treatment: State of the art – a summary. Waste Management 2002: The future of waste management in Europe, 7-8 October 2002, Strasbourg (France), VDI GVC (Düsseldorf, Germany).

Lapa, N., Santos Oliveira, J. F., Camacho, S. L. and Circeo, L. J. (2002) An ecotoxic risk assessment of residue materials produced by the plasma pyrolysis/vitrification (PP/V) process. Waste Management 22(3): 335-342.

Lemmens, B., Elslander, H., Vanderreydt, I., Peys, K., Diels, L., Oosterlinck, M. and Joos, M. (2007) Assessment of plasma gasification of high caloric waste streams. Waste Management

27(11): 1562-1569.

Limerick (2005) Feasibility Study of Thermal Treatment Options for Waste in the Limerick/Clare/Kerry region., from http://www.managewaste.ie/docs/WMPNov2005/FeasabilityStudy/LCK%20Thermal%20Feasibility%20Report-Ful%20%28web%29.pdf.

Malkow, T. (2004) Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. Waste Management 24(1): 53-79.

Minutillo, M., Perna, A. and Di Bona, D. (2009) Modelling and performance analysis of an integrated plasma gasification combined cycle (IPGCC) power plant. Energy Conversion and Management 50(11): 2837-2842.

Murphy, A. B. and Kovitya, P. (1993) Mathematical model and laser-scattering temperature measurements of a direct-current plasma torch discharging into air. Journal of Applied Physics 73(10): 4759-4769.

Murphy, A. B. and McAllister, T. (1998) Destruction of ozone-depleting substances in a thermal plasma reactor. Applied Physics Letters 73(4): 459-461.

Murphy, A. B. and McAllister, T. (2001) Modeling of the physics and chemistry of thermal plasma waste destruction. Physics of Plasmas 8(5): 2565-2571.

Nema, S. K. and Ganeshprasad, K. S. (2002) Plasma pyrolysis of medical waste. Current Science 83(3): 271-278.

Tang, L. and Huang, H. (2005) Thermal plasma pyrolysis of used tires for carbon black recovery. Journal of Materials Science 40(14): 3817-3819.

Taylor, R. (2009) Advanced Plasma Power. Swindon (United Kingdom), Personal communication.

Tendero, C., Tixier, C., Tristant, P., Desmaison, J. and Leprince, P. (2006) Atmospheric pressure plasmas: A review. Spectrochimica Acta Part B: Atomic Spectroscopy 61(1): 2-30.

Themelis, N. (2007) Thermal Treatment Review. Waste Management World July-August 2007.

UBA (2001). Draft of a German Report with basic informations for a BREF-Document “Waste Incineration“. Umweltbundesamt Berlin, from http://193.219.133.6/aaa/Tipk/tipk/4_kiti%20GPGB/63.pdf.

UllmannsEncyclopedia (2001) Ullmann's Encyclopedia of Industrial Chemistry. Kellersohn T. Weinheim, Wiley-VCH.

Van Oost, G., Hrabovsky, M., Kopecky, V., Konrad, M., Hlina, M., Kavka, T., Chumak, A., Beeckman, E. and Verstraeten, J. (2006) Pyrolysis of waste using a hybrid argon-water stabilized torch. Vacuum 80(11-12): 1132-1137.

Vanderreydt, I. (2010) VITO. Mol (Belgium), Personal communication.

Watanabe, T. and Shimbara, S. (2003) Halogenated hydrocarbon decomposition by steam thermal plasmas. High Temperature Material Processes 7(4): 455-474.

WPC (2010) Westinghouse Plasma Corporation. Retrieved 22 July, 2010, from http://www.westinghouse-plasma.com/.

Yamada, S., Shimizu, M. and Miyoshi, F. (2004) Thermoselect waste gasification and reforming process. JFE Steel Corporation Technical Report N° 3, July 2004.

Young, G. C. (2010) Municipal solid waste to energy conversion processes - Economic, Technical and Renewable Comparisons. New Jersey, John Wiley & Sons, Inc.